The Physiological and Perceptual Responses to Concurrent Training in Soccer Players

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ABSTRACT

This thesis was designed to enhance our understanding of the acute responses to small-sided games (SSG) and their integration into a concurrent training program along with resistance training (RT) in soccer. The first study characterised the neuromuscular, biochemical, endocrine, and perceptual responses to SSG training over 24-hours. The SSG (4vs4+goalkeepers; 6x7-min; 2-min inter-set recovery) induced immediate fatigue which persisted until the following morning. However, neuromuscular function presented a bimodal recovery pattern, whereby there was a temporary recovery at 2 hours post. Therefore, it was determined that the performance of a secondary training session at 2 hours post may not be compromised. The second study compared the responses to a day consisting of SSG training (single), versus a day consisting of SSG plus RT 2 hours later (double). The double training session resulted in further *small* impairments in neuromuscular, perceptual, and endocrine markers at 24 hours post training. The third study manipulated the order of SSG and RT and compared the performance of training and the 24-hour responses. This study found that whilst there were significant within-day differences in neuromuscular and endocrine markers, there were no differences at 24 hours post training. Furthermore, the order of SSG and RT did not affect the performance of SSG, but perceived exertion during RT was higher when performed after SSG training. This thesis provides a series of novel findings that enhance our understanding of the responses to SSG, the effects of performing multiple daily training sessions, and the effects of training order in soccer.

Key words: small-sided games, strength training, concurrent training, fatigue, recovery.

DECLARATIONS AND STATEMENTS

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed:[redacted]

Date: 14/06/2022

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

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I hereby give consent for my thesis, if accepted, to be available for photocopying and for inter- library loan, and for the title and summary to be made available to outside organisations.

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The University's ethical procedures have been followed and, where appropriate, that ethical approval has been granted.

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LIST OF ABBREVIATIONS

%HRR, percentage of heart rate reserve
1RM, one-repetition maximum
3RM, three-repetition maximum
ACTH, adrenocorticotrophic hormone
ADP, adenosine diphosphate
AFL, Australian Rules Football
AMPK, AMP-activated protein kinase
ANOVA, analysis of variance
AR, androgen receptors
ATP, adenosine triphosphate
AU, arbitrary units
BCAA, branched-chain amino acids
BLa, blood lactate
BW, body weight
C, cortisol
Ca^{2+}, calcium ions
CD, central defence
CK, creatine kinase
cm, centimetres
CM, central midfield
CMJ, countermovement jump
CNS, central nervous system
COD, change of direction
COM, centre of mass
CRH, corticotropin-releasing hormone
CV, coefficient of variation
E-C, excitation-contraction
EIMD, exercise induced muscle damage
EMG, electromyography
EPL, English Premier League
ES, effect size
FB, fullback
FFA, Free fatty acid
FIFA, Fédération Internationale de Football Association
FP, force platform
FT:CT, ratio of flight time to contraction time
FW, forward
G-force, gravitational force equivalent
g, grams
GK, goalkeeper
GPS, global positioning system
H^+, hydrogen ion
HFF, high-frequency fatigue
HIIT, high-intensity interval training
HR, heart rate
HSR, high-speed running
Hz, hertz
ICC, intraclass correlation coefficient

ITT, interpolated twitch technique
JH, jump height
K+, potassium ions
kg, kilograms
km, kilometre
$km \cdot h^{-1}$, kilometres per hour
KPI, key performance indicator
LFF, low-frequency fatigue
m, metres
$m{\cdot}s^{-1}$, metres per second
$m{\cdot}s^{-2}$, metres per second squared
$m \cdot min^{-1}$, meters per minute
MAS, maximal aerobic speed
MD, match-day
min, minutes
$mL \cdot kg^{-1} \cdot min^{-1}$, millilitres of oxygen used in one minute per kilogram of body weight
MP, mean power
mRFD, maximum rate of force development
ms, milliseconds
MSR, moderate speed running
mTOR, mechanistic target of rapamycin
MVC, maximum voluntary contraction
Na+, sodium ions
Na^{+}, sodium ions
NMJ, neuromuscular junction
PAP, post-activation potentiation
PCr, phosphocreatine
PF, peak force
Pi, inorganic phosphate
POMS, profile of mood state
PPO, peak power output
PV, peak velocity
r, Pearson's correlation coefficient
RE, running economy
RFD, rate of force development
RM, repetition maximum
RPE, rating of perceived exertion
RSA, repeated sprint ability
s, seconds
SD, standard deviation
SE, standard error
SHBG, sex hormone-binding globulin
SJ, squat jump
SM, speed endurance maintenance
SP, speed endurance production
SR, sarcoplasmic reticulum
SSC, stretch-shortening cycle
SSG, small-sided game
SSGs, small-sided games
SWD, smallest worthwhile difference

T, testosterone
T:C, testosterone to cortisol ratio
TD, total distance
TE, typical error
TMS, transcranial magnetic stimulation
VA, voluntary activation
vGRF, vertical ground reaction forces
VM, vastus medialis
VO_{2max}, maximal oxygen uptake
vs, versus
$W \cdot kg^{-1}$, watts per kilogram
WM, wide midfield
yr, years

Chapter 1.

General Introduction

1.1 INTRODUCTION

Soccer is not only widely regarded as the most popular sport in the world, but also the most studied, with the most associated research papers (Kirkendall, 2020). Performance in soccer is underpinned by a complex interaction between physical, physiological, psychological, technical, and tactical factors (Stølen et al., 2005; Bangsbo, 2015). It is likely that if one or more of these factors are inadequately developed or applied at both an individual and team level, then performance will be compromised. At elite and semi-professional levels, the pursuit for success continuously leads practitioners (e.g., coaches, sports scientists, psychologists, strength and conditioning staff) and researchers to find effective means to assess and improve these main areas of performance (Carling, 2012). Indeed, over the last five decades, studies have attempted to characterise the demands of competitive soccer in numerous ways, which, as with any evidence-based framework for sports performance, is key in supporting the design of appropriate training strategies (Bangsbo, Nørregaard, & Thorsø, 1991; Drust, Atkinson, & Reilly, 2000; Bradley et al., 2009).

With regards to the physical demands, soccer match-play is characterised as a prolonged intermittent sport that requires players to perform brief, high-intensity, linear and multi-directional activities interspersed by longer, variable periods of low to moderate-intensity activity (Stølen et al., 2005; Bangsbo, Mohr, & Krustrup, 2006; Rampinini et al., 2007b; Carling et al., 2008; Bush et al., 2015). Consequently, soccer players are required to develop and maintain multiple qualities aligned to successful performance, including but not limited to; strength, power, acceleration, speed, agility, aerobic capacity, and repeated sprint ability (RSA), as well as engage with technical and tactical training (Bangsbo, 1994b; Stølen et al., 2005). Due to the multifaceted match demands required, this usually results in concurrent training methods, with multiple sessions that target different adaptations often undertaken on the same day and within 24 hours of each other (Malone et al., 2015a; Martín-García et al., 2018b; Cross et al., 2019). However, for an athlete to positively adapt to training, the exercise stimulus should be applied in an order or a spacing that allows recovery to a time point where they are able to meet the demands of the following training session (Bishop, Jones, & Woods, 2008). Periods of functional overreaching may be strategically implemented in targeted periods (e.g., pre-season), whereby athletes will undertake a concentrated training block that results in a temporary loss of performance but then ‘rebound’ back and adapt after a planned realisation or recovery period (Meeusen et al., 2006a; Issurin, 2010). However, if training is continuously scheduled in a manner where athletes are not recovering between training sessions or matches, then there is a possibility that maladaptation, chronic fatigue, and overuse injury may occur (Morgans et al., 2014). Therefore, those responsible for the design of soccer training programs need to have an understanding of the demands and responses to each activity a player performs, whilst also considering factors that mitigate the possible interference effects of completing multiple training sessions sequenced within proximity to each other (Fyfe, Bishop, & Stepto, 2014; Doma, Deakin, & Bentley, 2017).

As the fixture demand is high in soccer (~40 – 50 matches over ~10 – 11 months) and there is often limited training time between these fixtures (~3 – 7 days), this leaves small windows of opportunity to target the multiple qualities required for the sport (Issurin, 2010; Morgans et al., 2014). Therefore, time-efficient training methods of simultaneously targeting the multiple qualities necessary for performance may be beneficial and warranted (Morgans et al., 2014; Turner & Stewart, 2014). One training method that has drawn considerable popularity, in both applied settings and in the literature, is the use of small-sided games (SSGs), which are characterised as any smaller format of competitive match-play by a reduction in player numbers and/ or pitch dimensions (Hill-Haas et a., 2011). Indeed, the popularity of SSGs as a training method is likely a result of their perceived ability to partly replicate some of the multifaceted demands of competition (Hill-Haas et al., 2011; Brandes, Heitmann, & Müller, 2012; Casamichana, Castellano, & Castagna, 2012). There is an abundance of literature investigating how manipulating the structural format of an SSG (e.g., playing area, number of players, rules, and conditions of the game) influences the playing intensity (Dellal et al., 2011a; Aguiar et al., 2012; Clemente et al., 2014a; Casamichana et al., 2015). Furthermore, it has been shown repeatedly that SSG training can stimulate similar aerobic adaptations to various forms of traditional interval training (Reilly & White, 2004; Impellizzeri et al, 2006; Hill-Haas et al., 2009a; Ali, 2011; Radziminski et al., 2013; Los Arcos et al., 2015; Moran et al., 2019; Kunz et al., 2019). However, to date, there is very limited research examining the impact of SSGs on the responses of soccer players in the hours and days that follow. This creates a gap in our current understanding of soccer training, considering the influence this may have on the performance and scheduling of additional training sessions within a training program. Therefore, the primary aim of the first experimental chapter in this thesis (chapter 4) will be to examine the physiological and perceptual responses to SSG training over a 24-hour period.

Strength and power are considered fundamental physical qualities in many sports, including soccer (Stølen et al., 2005; Silva, Gamble, 2006; Turner & Stewart, 2014; Silva, Nassis, & Rebelo, 2015). There is a considerable body of research examining the importance of these physical qualities, and how they underpin the performance of many key game demands in soccer, such as sprinting, kicking, tackling, heading, accelerating, and changing direction (Wisloff et al., 2004; Wing, Turner, & Bishop, 2018; Northeast et al., 2019; Boraczyński et al., 2020). Furthermore, there is convincing evidence that greater strength diminishes the number and severity of injuries in team sport (Lehnhart et al., 1996; Croisier et al., 2008; Opar et al., 2015; Timmins et al., 2016). As a result of these benefits, elite soccer teams often schedule resistance training on the same day as soccer training, and most commonly, resistance training follows field training (Cross et al., 2019). However, the impact of performing a second daily training session in soccer is unknown. Therefore, the aim of chapter 5 will be to examine the physiological and perceptual responses to a training day consisting of a single SSG training session, in comparison to a day consisting of a double training session (i.e., SSG and resistance training).

The concurrent training paradigm has long been associated with an 'interference effect', whereby attenuated strength and power or aerobic adaptation may occur in comparison to those following resistance or endurance training alone (Wilson et al., 2012; Fyfe, Bishop, & Stepto, 2014; Eddens, van Someren, & Howatson, 2018; Doma et al., 2019; Lee et al., 2020). Whilst the underlying mechanisms of the interference effect are likely multifactorial, possible reasons highlighted in previous literature involve residual fatigue (i.e., inhibition in the performance of training) (Doma, Deakin, & Bentley, 2017), conflicting hormonal profiles (Bell et al., 2000), and incompatible molecular signalling pathways (Atherton et al., 2005; Spiering et al., 2008b; Hawley, 2009). However, with correct exercise sequencing and programming, there is evidence that separate bouts of training performed on the same day but with sufficient recovery time, can result in elevated performance, which is likely due to acute changes in circulating hormone concentrations (Ekstrand et al., 2013; Cook et al., 2014; Russell et al., 2016a), or a phenomenon known as post-activation potentiation (PAP) (Hodgson, Docherty, & Robbins, 2005; Wilson et al., 2013). Furthermore, it is thought that factors such as training modality, volume, intensity, between-session recovery time, and session order can influence both the acute responses and chronic adaptations to concurrent training (Sale et al.,1990; Wilson et al., 2012; Doma & Deakin, 2013; Enright et al., 2015; Robineau et al., 2016; Johnston et al., 2017; Lee et al., 2020). However, the literature in this area is often conflicting, and many studies have recruited amateur or recreational athletes (Sale et al., 1990; Robineau et al., 2016; Fyfe et al., 2016; Lee et al., 2020), and these results cannot necessarily be generalised to well-trained soccer players. Furthermore, training studies have typically assessed traditional modes of aerobic or endurance training (e.g., continuous or interval cycling or running) combined with various forms of resistance training (Sale et al., 1990; Robineau et al., 2016; Fyfe et al., 2016; Lee et al., 2020). Consequently, the acute interactions between on-field and resistance training in team sport are not well understood, which is problematic considering the prevalence of such practices in applied settings (Jones et al., 2016a; Cross et al., 2019). Therefore, the primary aim of experimental chapter 6 in this thesis will be to investigate the acute interactions between same-day SSG and resistance training in soccer. More specifically, to compare the effects of manipulating the order of SSG and resistance training on the neuromuscular, endocrine, and perceptual responses over 24 hours.

The factors discussed above create an important challenge for those responsible for designing soccer training programs, and athletes will be experiencing a continuous cycle of physical loading, fatigue, recovery, and adaptation. A well-designed training program should strive to find an optimal balance between these factors (Morgans et al., 2014; Turner & Stewart, 2014; Walker & Hawkins, 2017). Furthermore, as variations in the fixture schedule may occur during a season (e.g., cup competitions) and training and competition demands may vary due to a multitude of factors (e.g., player work-rate, tactical approaches, coaching changes, travel, injury, and lifestyle factors), being able to monitor the performance and fatigue status of each athlete with reliable and valid methods is imperative. This provides performance and coaching staff with objective data to inform the decision-making process on training and recovery strategies, with the aim of maintaining and optimising performance throughout a season (Akenhead & Nassis, 2016; Thorpe et al., 2017). Indeed, methods such as the use of global positioning systems (GPS) to measure external demands, and various monitoring techniques to assess the responses to exercise (e.g., neuromuscular performance, biomarkers, subjective questionnaires) are commonplace in elite soccer (Akenhead & Nassis, 2016; Thorpe et al., 2017). However, using these methods to investigate the performance of or responses to SSG training and their integration into a concurrent training program is not well understood. Therefore, this thesis has been designed to broaden and enhance our understanding of concurrent training in soccer. Briefly, the primary aims of this thesis will be to:

- Characterise the neuromuscular, endocrine, biochemical, and mood responses to SSG training over a 24-hour period
- Compare the 24-hour responses to a training day consisting solely of SSG training, versus a training day consisting of SSGs with the addition of a resistance training session 2 hours later.
- Investigate the acute performance and fatigue effects of manipulating the order of SSG and resistance training over 24 hours.

Chapter 2.

Review of Literature

2.1 REVIEW OF LITERATURE INTRODUCTION

The following literature review is separated into nine main sections. Each section will be written with the aim of providing a theoretical background to this thesis and to justify why the series of studies have been conducted:

- As competition performance is ultimately the overarching activity practitioners are trying to improve, the first section (2.2) will provide a comprehensive background on the demands of competitive soccer. Here, the interaction between the combination of factors that underpin performance will be discussed. This section will be written to provide a foundation for the subsequent sections.

- Section 2.3 will review the current literature on soccer training. This section will highlight the challenges of structuring soccer training and discuss our current understanding of its organisation. Then, this section will progress into a specific focus on the efficacy of SSGs as a training method, and how manipulation of multiple variables can affect the demands and the immediate physiological responses. Moreover, the previously reported demands of SSGs in comparison to 11 vs 11 matches and traditional modes of interval training will be discussed. Finally, this section will review the literature regarding strength and power in soccer and how these qualities underpin performance.

- Section 2.4 will examine the common methods used to quantify the external physical demands in team sports. Here, there will be a particular focus on how GPS devices are predominantly used in soccer, and its reliability and validity in detecting the key training and game demands highlighted in sections 2.2 and 2.3.

- Section 2.5 will review the literature regarding neuromuscular fatigue and highlight the various mechanisms that may be responsible for a loss of performance. Furthermore, this section will review previous studies that have assessed the neuromuscular response after soccer specific activity.

- Section 2.6 will discuss the role of the endocrine system on acute changes in neuromuscular performance and the chronic adaptations to exercise.

- Section 2.7 will discuss the benefits and limitations of previous methods used to monitor neuromuscular function in both laboratory and applied settings. Furthermore, other common strategies used to monitor fatigue and recovery will be reviewed.

- Section 2.8 will review the literature regarding the acute responses to soccer and resistance training. Then, how the combination of training modes (i.e., concurrent training) may interact, and importantly, how manipulating the organisation of training may influence the acute responses and chronic adaptations to concurrent training.

- Summaries and conclusions from the review will be provided in section 2.8. Here, the gaps in the literature will be identified which provides justification for the development of the research questions in this thesis.

- Finally, taking all this information together, section 2.10 will specify the aims and objectives of the experimental chapters and list the specific questions this thesis hopes to answer.

2.2 DEMANDS OF COMPETITIVE SOCCER

Performance in soccer is determined by a complex interaction between a multitude of factors (Bangsbo, 2015). Over the last five decades, the demands of soccer matches have been well documented, with several methodological systems used and key variables highlighted to quantify match demands (Carling et al., 2008; Sarmento et al., 2014). Early work in this area predominantly relied on video-based notational analysis, however, the more recent development of computerised multi-camera tracking and GPS has circumvented the more traditional methods (see section 2.4.2 for a review of tracking methods). A comprehensive understanding of the match demands can inform better training prescription, as training programs can be tailored according to the specific demands and the differences commonly observed across playing positions (Carling, 2013). For the purpose of this review and the subsequent experimental chapters, there will be a primary focus on the physical and physiological demands of soccer. However, there is a dynamic interaction between the key factors highlighted (i.e., physical, physiological, psychological, technical, and tactical), all of which underpin performance in soccer (Rampinini et al., 2008). Therefore, these relationships will also be discussed, albeit more briefly, within this section of the review.

2.2.1 Physical demands of matches

Soccer match-play is characterised as a prolonged intermittent sport that requires players to perform brief, high-intensity linear and multi-directional activities interspersed by longer, variable periods of low to moderate-intensity recovery periods (Bangsbo, Mohr, & Krustrup, 2006; Rampinini et al., 2007b; Carling et al., 2008). Despite the various methods used to evaluate the activity profiles of soccer players, it is consistently reported that elite outfield players will typically cover between 9 – 13 km of total distance throughout a 90-min match, which is dependent on playing position (Table 1; Mohr, Krustrup, & Bangsbo, 2003; Bradley et al., 2009; Sarmento et al., 2014). The majority of this distance (>70%) is covered during low-intensity activity such as walking and jogging (Mohr, Krustrup, & Bangsbo, 2003; Bangsbo, Mohr, & Krustrup, 2006), and these periods are necessary to facilitate recovery between the high-intensity explosive actions that often determine the outcome of matches (Helgerud et al., 2001; Stølen et al., 2005). A study by Faude and colleagues (2012) reported that out of a sample of 360 goals scored during the 2007/08 German Bundesliga season, the majority (83%) were preceded by at least one ‘powerful’ action by the scoring or assisting player. Although analysed subjectively, these powerful actions included linear sprints, change of direction (COD) sprint, jumps, rotation (around the centreline of the body), or a combination of those actions. Furthermore, the authors reported that the most frequent action for the scoring player was a linear sprint, which was involved in 45% of goals (Faude, Koch, & Meyer, 2012). Therefore, it seems prudent that many previous studies have focused on the number of efforts or distance covered during high-speed running (HSR) and sprinting activities. Furthermore, previous researchers have suggested that these parameters are important markers of physical performance due to their strong relationship with training status and physical capacity (Krustrup et al., 2003; Krustrup et al., 2005; Bradley et al., 2009). The thresholds at which these activities are classified vary considerably between studies (Table 1 & Table 7), but given a common HSR band of 19.8 – 25.2 $km \cdot h^{-1}$ (or 5.5 – 7.0 $m \cdot s^{-1}$) and a sprinting threshold of ≥25.2 $km \cdot h^{-1}$ (or ≥7.0 $m \cdot s^{-1}$), elite players will typically cover between ~500 – 1200 m of HSR and ~100 – 450 m of sprinting, which is dependent on playing position (Table 1). Relative to the overall distance covered by players, ~5 – 13% is covered during HSR and ~1 – 4% whilst sprinting (Bradley et al., 2009; Di Salvo et al., 2010). Highlighting the importance of HSR ability for the contemporary player, Barnes et al. (2014) examined the evolution of the physical demands across a seven-season period (2007/07 – 2012/13) in the English Premier League (EPL). The authors observed that HSR (19.8 – 25.2 $km \cdot h^{-1}$) and sprinting (>25.2 $km \cdot h^{-1}$) distances have increased substantially (~30 – 50%), with the number of sprint efforts increasing by ~85%. This also coincided with increases in technical actions, with more passes (35 ± 17 vs 25 ± 13) and successful passes (83 ± 10% vs 76 ± 13%) in 2012/13 compared to 2006/07. Thus, players must be athletic and robust enough to cope with these physical demands whilst maintaining technical proficiency, which has important implications for training design.

However, a primary focus on total, HSR and sprinting distances omits several key match activities such as changing direction, accelerating, decelerating, jumping, tackling, and kicking. It has been observed that elite players will perform ~150 – 250 of these brief but intense actions throughout a game (Mohr, Krustrup, & Bangsbo, 2003). These actions are known to be metabolically and mechanically taxing when repeated (Osgnach et al., 2010; Gaudino, Alberti, & Iaia, 2014; Nedelec et al., 2014) as well as being important in influencing performance and match outcome (Faude, Koch, & Meyer, 2012). Through the more recent development of GPS devices sampling at higher frequencies (e.g., >5 Hz), and with the integration of triaxial accelerometers, further insight into these parameters can be gained (see section 2.4.5 for review). Due to the intermittent and multidirectional demands of soccer requiring regular changes of speed and direction, acceleration and deceleration activity has drawn particular focus in both literature and practical settings (Akenhead & Nassis, 2016). These parameters are associated with critical activities in soccer, such as being first to the ball and creating or stopping goal-scoring opportunities (Carling et al., 2008). Acceleration is a distinct physical quality and requires a higher rate of force development, energy expenditure, and neural activation compared to running at a continuous speed (Mero & Komi, 1987; di Prampero et al., 2005; Osgnach et al., 2010). Additionally, decelerations involve high-force eccentric muscle contractions, which have the potential to result in muscle damage, mechanical and metabolic fatigue (Butterfield, 2010; Thorpe & Sunderland, 2012). Whilst acceleration is clearly a precursor to HSR, Varley and Aughey (2013) reported that high-intensity accelerations (defined as a change in velocity ≥2.78 $m \cdot s^{-2}$) occurred ~8 times more frequently than sprint efforts (defined as a velocity ≥6.94 $m \cdot s^{-1}$) in 29 elite soccer players over 34 competitive matches. Furthermore, in this study, ~85% of the accelerations registered did not advance into a HSR effort (defined as a velocity ≥4.17 $m \cdot s^{-1}$) (Varley & Aughey, 2013). In support of these findings, researchers who have incorporated acceleration-related workload parameters (e.g., the distance covered in specific acceleration and deceleration thresholds), have highlighted that an ~6 – 8% underestimation in workload may result from monitoring distance and speed alone (Osgnach et al., 2010; Gaudino et al., 2013). However, it should be noted that the reliability and validity of measuring accelerations and decelerations with GPS devices has been questioned, particularly when the change in velocity exceeds 3 $m \cdot s^{-2}$ (Akenhead et al., 2014; Buchheit et al., 2014a). Furthermore, variability and inconsistency in these variables between GPS manufacturers have been reported (Thornton et al., 2018), making comparisons between studies and athletes problematic. There are many different variables to be considered in match performance analyses, so finding metrics that are valid, reliable, and appropriate for the environment is imperative. A full review of the various match analyses techniques and the metrics that have received focus in previous literature is provided in section 2.4.

2.2.2 Positional differences

As alluded to previously, there are differences in the physical demands across the various playing positions in soccer (Table 1). Typically, these positions are divided into six categories: goalkeeper (GK), central defender (CD), fullback (FB), central midfielder (CM), wide midfielder (WM), and forward (FW) (Table 1). It is consistently reported that CDs perform significantly less total distance and HSR than all other positions (Table 1). However, their role in the team is predominantly more combative than other positions, with a relatively high proportion of their physical load likely being derived from duels and impacts (e.g., tackles, headers, and body contacts) (Bloomfield et al., 2007; Dellal et al., 2010b; Arrones et al., 2014; Torrenno et al., 2016). These actions can potentially induce muscle damage and impair neuromuscular function, irrespective of running demands (Bloomfield et al., 2007). Previous research generally shows that CM players cover the most total distance, and CM, FB and WM players cover more HSR compared to other positions (Barros et al., 2007; Di Salvo et al., 2007; Bradley et al., 2009; Di Salvo et al., 2009). Several reasons may explain why these positional differences in locomotive patterns exist, which is highly influenced by the tactical nature of each role and the playing formation of the team (Bradley et al., 2011; Tierney et al., 2016; Aquino et al., 2018). Nevertheless, some studies have shown that positional differences in physical and physiological capacity exist, with CM and FB players possessing greater maximal oxygen uptake (VO_{2max}) in laboratory tests (Reilly, Bangsbo & Franks, 2000), and performing better in intermittent running tests (Reilly et al., 2000; Mohr, Krustrup, & Bangsbo, 2003) compared to other positions. With regards to sprinting distance ($\geq$25.2 $km \cdot h^{-1}$), the lateral positions (i.e., FB & WM) along with FW positions typically perform the greatest distance (Table 1; Bradley et al., 2009; Di Salvo et al., 2009; Reinhardt et al., 2020). Furthermore, these positions have been shown to reach the highest maximum velocity during matches (Bradley et al., 2010). This may be explained due to the lateral players having more time and space on the flanks of the pitch to fully accelerate, or the FW players having more space to make attacking runs (i.e., behind the opposition defenders). Furthermore, it is plausible to suggest that acceleration ability and maximal speed are key attributes for these positions, which dictates their talent identification and selection in the team (Ferro et al., 2014). Both factors likely contribute to the differences seen in sprint distance and maximal velocity across playing positions. Table 1 provides a summary of key studies that have assessed the physical demands and positional differences in soccer match-play.

Table 1. Summary of key studies that have assessed the physical demands across different playing positions and levels during competitive 11 vs 11 soccer matches.

Study	Sample	Tracking method	Variable (mean ± SD)			Key findings
Mohr, Krustrup, & Bangsbo (2003)	18 elite male Italian first division players & 24 professional Danish first division players (7 games per team).	Video analysis (manual coding).	**Total dist.** CB 9740 ± 220 m FB 10980 ± 230 m MF 11000 ± 210 m FW 10480 ± 300 m	**HSR dist. (15-18 km·h^{-1})** CB 1690 ± 100 m FB 2460 ± 130 m MF 2230 ± 150 m FW 2280 ± 140 m	**SPR dist. (>18 km·h^{-1})** CB 440 ± 30 m FB 640 ± 60 m MF 440 ± 40 m FW 690 ± 80 m	- MF, FB & ATT covered more total dist. than CB ($p < 0.05$). - MF, FB & ATT covered more HSR dist. than CB ($p < 0.05$). - FB & ATT covered more SPR dist. than CB & MF ($p < 0.05$).
Bradley et al. (2009)	28 men's EPL games across the 2005/06 season (observations = 370).	Multi-camera computerised tracking system (Prozone) (10 Hz).	**Total dist.** CB 9885 ± 555 m FB 10710 ± 589 m CM 11450 ± 608 m WM 11535 ± 933 m FW 10314 ± 1175 m	**HSR dist. (19.8-25.2 km·h^{-1})** CB 603 ± 132 m FB 984 ± 195 m CM 927 ± 245 m WM 1214 ± 251 m FW 955 ± 239 m	**SPR dist. (>25.2 km·h^{-1})** CB 152 ± 50 m FB 287 ± 98 m CM 204 ± 89 m WM 346 ± 115 m FW 264 ± 87 m	- CM & WM covered more total dist. than all other positions ($p < 0.05$). - WM covered more HSR dist. than all other positions ($p < 0.05$). - FB & WM covered greater SPR dist. than all other positions ($p < 0.01$).
Di Salvo et al. (2009)	563 male EPL players over 3 seasons (2003 - 2006) (observations = 7355).	Multi-camera computerised tracking system (Prozone) (10 Hz).	–	**HSR dist. (19.8-25.2 km·h^{-1})** CB 681 ± 128 m FB 911 ± 123 m CM 928 ± 124 m WM 1049 ± 106 m FW 968 ± 143 m	**SPR dist. (>25.2 km·h^{-1})** CB 167 ± 53 m FB 238 ± 55 m CM 217 ± 46 m WM 260 ± 47 m FW 262 ± 63 m	-WM covered more whilst CB covered less HSR dist. than all other positions ($p < 0.05$). - WM & ATT covered more SPR dist. than FB, CM & CB whilst FB covered greater SPR dist. than CM & CB. CB covered less SPR dist. than all other positions ($p < 0.05$).
Dellal et al. (2010b)	Elite male French first division players over the 2005/06 season (observations = 5938).	Multi-camera computerised tracking system (Amisco pro) (25 Hz).	**Total dist.** CB 10426 ± 808 m FB 10656 ± 860 m CDM 11501 ± 901 m CAM 11726 ± 984 m WM 12030 ± 978 m FW 10943 ± 979 m	**HSR dist. (21-24 km·h^{-1})** CB 230 ± 56 m FB 274 ± 63 m CDM 302 ± 69 m CAM 335 ± 62 m WM 336 ± 64 m FW 300 ± 57 m	**SPR dist. (>24 km·h^{-1})** CB 199 ± 66 m FB 241 ± 70 m CDM 221 ± 76 m CAM 235 ± 72 m WM 235 ± 85 m FW 290 ± 75 m	- CDM, CAM & WM covered more total dist. than all other positions ($p < 0.05$). - WM & CAM covered more whilst CB & FB covered less HSR dist. than the other playing positions ($p < 0.05$). - ATT covered more whilst CB covered less SPR dist. than all other playing positions ($p < 0.05$).

Varley & Aughey (2013)	29 elite male Australian first division players over 34 matches during the 2010/11 season (observations = 126).	5 Hz GPS devices (SPI Pro, GPSports).	**HI ACC (>2.78 m·s^{-2})** CB 56 ± 18 FB 90 ± 15 CM 60 ± 20 WM 65 ± 18 FW 69 ± 19	**HI efforts (15-25 km·h^{-1})** CB 104 ± 28 FB 156 ± 22 CM 125 ± 41 WM 141 ± 31 FW 127 ± 23	**SPR efforts (>25 km·h^{-1})** CB 5 ± 3 FB 12 ± 5 CM 4 ± 4 WM 8 ± 4 FW 14 ± 6	- FB performed more whilst CB less HI ACC than all other positions (p <0.05). - FB performed more HI efforts than CB & CM (p <0.05). - WM performed more HI efforts than CB & ATT (p <0.05). - FB & ATT performed more SPR efforts than all other positions (p <0.05). - CB & CM performed less SPR efforts than all other positions (p <0.05).
Ade, Fitzpatrick, & Bradley, (2016)	20 male EPL players in 46 games over consecutive seasons (2010/110 – 2013/14) (observations = 100).	Multi-camera computerised tracking system (Amisco pro) (25 Hz).	**RHIE efforts** CB 1.7 ± 1.4 FB 3.6 ± 2.6 CM 2.9 ± 1.6 WM 5.2 ± 3.4 FW 3.4 ± 2.1	**HI efforts (>21 km·h^{-1})** CB 20.3 ± 6.5 FB 30.6 ± 10.2 CM 29.4 ± 9.3 WM 38.7 ± 14.4 FW 33.6 ± 10.0	**Mean HI effort dist.** CB 16.6 ± 3.0 m FB 20.2 ± 2.6 m CM 18.5 ± 2.8 m WM 20.3 ± 3.5 m FW 17.8 ± 2.2 m	- WM performed more HI efforts than CB, FB & CM (ES: >0.6). - CB performed less HI efforts compared to all other positions (ES: >0.6). - WM performed more RHIE efforts than CB, CM & ATT (ES: >0.6). - CB performed less RHIE efforts than all other positions (ES: >0.6).
Martín-García et al. (2018a)	23 young professional males from Spanish 2nd division over 37 games (2015/16) (observations = 605).	10 Hz GPS devices (STATSports Viper Pod)	**Most intense 1-min period total dist. (m·min^{-1})** CB 181.9 ± 16.4 m·min^{-1} FB 195.3 ± 15.7 m·min^{-1} CM 204.0 ± 19.0 m·min^{-1} WM 201.1 ± 19.0 m·min^{-1} FW 180.9 ± 20.4 m·min^{-1}	**Most intense 1-min period HSR dist. (>19.8 km·h^{-1}) (m·min^{-1})** CB 47.2 ± 19.3 m·min^{-1} FB 55.9 ± 20.2 m·min^{-1} CM 45.2 ± 22.6 m·min^{-1} WM 48.3 ± 16.4 m·min^{-1} FW 49.4 ± 16.4 m·min^{-1}	**Most intense 1-min period SPR dist. (>25.2 km·h^{-1}) (m·min^{-1})** CB 19.1 ± 20.5 m·min^{-1} FB 18.3 ± 18.1 m·min^{-1} CM 12.7 ± 17.2 m·min^{-1} WM 11.4 ± 12.5 m·min^{-1} FW 18.8 ± 16.6 m·min^{-1}	- In most intense 1-min period, FB, CM & WM covered greater total distance per minute than CB & FW (p <0.001). - No significant differences for most intense 1-min period for HSR distance per minute across positions (p= 0.069). - No significant differences for most intense 1-min period for SPR distance per minute across positions (p= 0.085).
Reinhardt et al. (2020)	55 sub-elite male players competing in German 4th & 5th divisions over consecutive seasons (2016/17 – 2018/19) (observations = 485).	10 Hz GPS devices (Polar Team Pro, Polar Electro).	**Total dist.** CB 9212 ± 457 m FB 9757 ± 254 m CM 10760 ± 588 m WM 10417 ± 375 m FW 9586 ± 499 m	**HSR dist. (21-24 km·h^{-1})** CB 350 ± 60 m FB 548 ± 78 m CM 555 ± 164 m WM 689 ± 121 m FW 528 ± 108 m	**SPR dist. (21-24 km·h^{-1})** CB 84 ± 31 m FB 166 ± 45 m CM 97 ± 41 m WM 237 ± 79 m FW 170 ± 84 m	- CM performed more whilst CB performed less total dist. than all other positions (p <0.05). - WM performed more whilst CB performed less HSR dist. than all other positions (p <0.05). - WM performed more whilst CB & CM performed less SPR dist. than all other positions (p <0.05).

Abbreviations: CB, centre back; FB, full back; CM, central midfield; CDM, central defensive midfield; CAM, central attacking midfield; WM, wide midfielder; FW, forward; dist, distance; HSR, high-speed running; SPR, sprinting; HI, high-intensity; ACC, accelerations; RHIE, repeated high-intensity efforts (minimum of 2 efforts separated by a maximum of 20 s recovery).

2.2.3 Relationship between match output and playing standard

Previous research comparing the relationship between HSR data and team performance is equivocal. Several studies have reported that players competing at a higher level perform more HSR than those at a lower level (Ekblom, 1986; Bangsbo, Norregaard, & Thorso, 1991; Mohr et al., 2008; Ingebrigtsen et al., 2012). For example, an early study by Mohr, Krustrup, and Bangsbo (2003) compared moderate-speed running (MSR) distances (15 – 18 km·h^{-1}) between an elite Italian team competing in Champions League against a sub-elite team competing in Danish first division. The authors reported that on average, the elite players performed ~28% more MSR than the sub-elite players (2430 ± 140 m vs 1900 ± 120 m) (Mohr, Krustrup, & Bangsbo, 2003). However, this study examined match running performance in only 18 elite and 24 sub-elite players over seven games, and the teams were competing at vastly different standards in different countries. Furthermore, the activities were quantified via video-based manual coding, which is likely to be prone to human error. A pair of more recent studies including 563 players in the top professional league in England (Di Salvo et al., 2009) and 186 players in Italy (Rampinini et al., 2009a) investigated the relationship between physical output and final league ranking. Both studies found that lower-ranked teams in each league covered significantly greater distances at high-intensity running thresholds. In EPL players, the distances covered at speeds between 19.8 – 25.2 km·h^{-1} and ≥25.2 km·h^{-1} were significantly greater in both middle to bottom-ranked teams in comparison to their top-five ranked counterparts ($p < 0.05$) (Di Salvo et al., 2009). In the Italian Serie A League, similar findings were reported in players competing for the five highest-ranked teams in comparison to the five lowest-ranked teams (Rampinini et al., 2009a). In this study, the distances covered in the bottom five teams at thresholds ≥14.0 km·h^{-1} and ≥19.0 km·h^{-1} were 11% and 9% higher ($p < 0.01$) than the highest ranked teams, respectively. Bradley et al. (2013) compared the physical outputs in the top three divisions in England (EPL vs Championship vs League 1) and reported that those in the lower leagues (i.e., Championship and League 1) performed significantly more total, HSR (19.8 – 25.2 km·h^{-1}) and sprinting distances (≥25.2 km·h^{-1}) than their Premier League counterparts, irrespective of playing position ($p < 0.01$). These differences were despite no significant differences in intermittent running performance (i.e., Yo-Yo intermittent endurance test level 2) measured between the leagues. However, in the same study, technical indicators (i.e., total passes, successful passes, forward passes, balls received and touches per possession) were significantly higher in the Premier League players compared to the lower division players ($p < 0.01$) (Bradley et al., 2013). There are several feasible explanations for the discrepancy between findings in this area. Firstly, many of the studies that reported significantly greater physical outputs at higher vs lower standards of play were conducted in various elite and sub-elite Scandinavian leagues. It may be that when similar methods are applied in countries where there are multiple full-time elite leagues (e.g., England and Italy), this relationship reverses due to less variation in the competition level and training status between leagues. Secondly, the previously mentioned studies in the EPL (Di Salvo et al., 2009) and Italian first division (Rampinini et al., 2009a) that reported differences in the distance covered at high-speed between successful and less-successful teams, also identified large discrepancies in efforts concerning time spent in and out of possession of the ball. Indeed, the frequency of ball possessions, short and long passes completed, shots, and shots on target were also higher in the more successful Italian teams (Rampinini et al., 2009a). The greater high-speed activity observed in the lower-ranked teams here could be a consequence of their inability to maintain ball possession and attempt to regain it when lost. This theory may also go some way in explaining the differences reported between the top three English leagues by Bradley et al. (2013). Taken together, these studies highlight the complexity of match running demands and suggests that analysis of HSR data alone does not discriminate between 'successful' and 'unsuccessful' teams. It seems that other factors, such as technical and tactical effectiveness, playing style, time in possession and other contextual factors are likely to have an important influence on both the physical demands and the game outcome.

2.2.4 Aerobic demands

Due to the length of a match (≥90-min) and the prolonged periods of low-intensity activity, the aerobic system is the predominant energy pathway in soccer, and it is estimated that ~90% of player energy is provided by aerobic metabolism (Stølen et al., 2005). Most previous studies report an average heart rate (HR) of ~80 – 90% of maximum values (HR_{max}) over the course of a match, which equates to an exercise intensity close to the anaerobic threshold in soccer players (Stølen et al., 2005). This corresponds to an average oxygen uptake of ~70 – 75% of VO_{2max} (Bangsbo, Mohr, & Krustrup, 2006; Reilly, 2007; Krustrup et al., 2011). A systematic review of 25 studies conducted in elite male players revealed mean VO_{2max} values of ~59 $mL \cdot kg^{-1} \cdot min^{-1}$ (range, 52.1 – 67.6 $mL \cdot kg^{-1} \cdot min^{-1}$), and these values remained relatively stable over the three decades in which the studies were published (i.e., 1975 – 2012) (Shalfawi & Tjelta, 2016). Some studies have reported significant relationships between aerobic capacity and the total distance covered during matches (Impellizzeri et al., 2006; Krustrup et al., 2003;

Krustrup et al., 2005; Rampinini et al., 2007a). For example, a training intervention study by Helgerud et al. (2001) suggested that an increase in VO_{2max} from 58.1 to 64.3 $mL \cdot kg^{-1} \cdot min^{-1}$ (+10.8%) resulted in a 20% increase in the distance covered during a match. However, these correlations do not necessarily indicate causation, and it is possible that the increased total distance during matches is driving the increase in VO_{2max}, rather than vice versa. Furthermore, these results may be misleading without considering the contextual variables (e.g., tactics, possession, game status, environment) that influence the total distance covered during games. Indeed, the total distance covered by a team is a poor indicator of success (Carling, 2013). In support of this, Arnason et al. (2004) reported no relationship between VO_{2max} and final league standing in the top 20 ranked teams in Iceland. Furthermore, in a study of 1545 male players over a 23-year period (1989 – 2012), Tønnessen and colleagues (2013) did not find any significant differences in VO_{2max} between international, first division, second division and junior players. Nevertheless, a well-developed aerobic capacity undoubtedly supports the high-intensity intermittent nature of the game, with rapid VO_2 kinetics required to facilitate the recovery between repeated high-intensity bouts (e.g., hydrogen ion [H^+] buffering, enhanced phosphocreatine [PCr] regeneration) (Tomlin & Wenger, 2001). Previous researchers have suggested a VO_{2max} of ~60 $mL \cdot kg^{-1} \cdot min^{-1}$ represents a minimum threshold in which players possess the physiological attributes for success in elite men's soccer (Reilly, Bangsbo, & Franks, 2000; Tønnessen et al., 2013; Shalfawi & Tjelta, 2016). Beyond this baseline, other physical qualities such as linear sprinting speed, agility, and RSA are suggested to be more influential in performance (Impellizzeri et al., 2008; Kaplan, Erkmen, & Taskin, 2009; Haugen, Tønnessen, & Seiler, 2012). Indeed, a study by Rampinini et al. (2009b) reported that professional players performed better than well-trained amateur players in a RSA test with a directional change (i.e., 6 x 40 m shuttles, with 20 s recovery), despite similar VO_{2max} values between groups. Therefore, it is suggested that VO_{2max} may not be the most suitable indicator of aerobic fitness in soccer players as they typically train for intermittent, rather than continuous exercise (Drust, Reilly, & Cable, 2000; Bangsbo, Mohr, & Krustrup, 2006; Krustrup et al., 2006). It is likely that rapid VO_2 kinetics and H^+ buffering capacity are more important determinants of RSA performance than VO_{2max} (Bailey et al., 2009; McKay, Paterson, & Kowalchuk, 2009**;** Rampinini et al., 2009b). Thus high-intensity interval training (HIIT) is often a recommended training method to align with the intermittent demands of the game (Rampinini et al., 2009b).

2.2.5 Anaerobic demands

Although aerobic metabolism dominates the energy provision during a match, the most decisive actions (e.g., sprints, shots, tackles, jumps) rely on anaerobic metabolism (Helgerud et al., 2001; Stølen et al., 2005). Rapid duration high-intensity activities (~ <10 s) performed infrequently predominantly rely on the ATP–PCr pathway to provide energy (Baker, McCormick, & Robergs, 2010). Anaerobic glycolysis becomes more prominent when activities are more frequent and/ or longer in duration (~10 – 120 s) (Baker, McCormick, & Robergs, 2010). Muscle biopsies performed during matches have reported PCr values of ~70% of those at rest, however, these are possibly much lower (e.g., <30% of resting values) if taken immediately after the most intense periods of play (Krustrup et al., 2006; Bangsbo, Iaia, & Krustrup, 2007). However, this is hard to confirm given the uncontrolled nature of match-play and the delay between cessation of exercise and extraction of muscle tissue in these studies. Normal blood lactate (BLa) concentrations reported at the end of each half typically range between 2 – 10 $mmol.L^{-1}$, with individual values reported as high as 12 $mmol.L^{-1}$ (Ekblom, 1986; Bangsbo, Norregaard, & Thorso, 1991; Bangsbo, 1994b; Roi et al., 2004; Krustrup et al., 2006; Aslan et al., 2012). However, it is important to note that BLa concentration in soccer is largely influenced by the activity pattern of the individual player during the 5-min period prior to blood sampling, which likely explains the large variation in results (Bangsbo et al., 1991; Krustrup et al., 2006). In addition, it appears that BLa concentrations are higher in the first half compared to the second half (Figure 1), which may be related to the reduced distances and intensities commonly seen in the second half compared to the first (Bangsbo et al., 1991; Mohr et al., 2003; Stølen et al., 2005). Furthermore, it seems that elite players rely on anaerobic energy pathways more than non-elite players (Figure 1), which may be related to increased intensity of play at a higher level (Stølen et al., 2005). Supporting these findings, positive relationships (r = 0.72 – 0.80) between HSR outputs during the peak 5-min periods of play and the ability to perform high-intensity exercise with a large anaerobic contribution (i.e., Yo-Yo intermittent recovery test level 2) has been reported (Bangsbo, Iaia, & Krustrup, 2008; Mohr et al., 2016b).

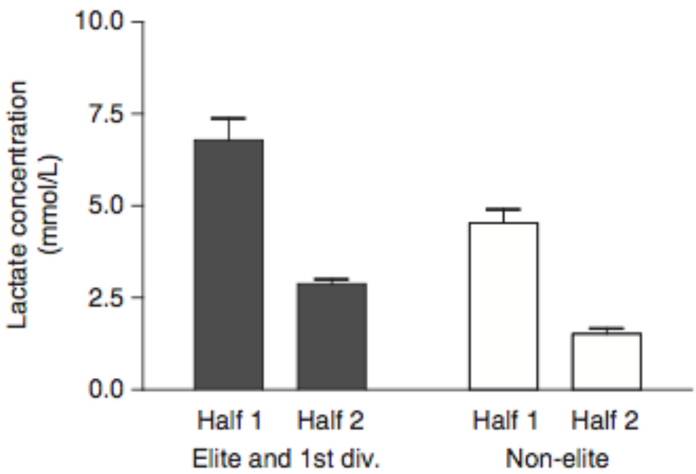

Figure 1. Blood lactate concentrations in elite and non-elite soccer players during the two halves during a match. Data reproduced from Stølen et al. (2005). Div. = division.

2.2.6 Match-related fatigue

Many previous studies in soccer have divided time-motion analyses data into distinct timeframes to establish cumulative declines in work rate as the match progresses, or transient declines after intense periods of play. Time periods examining these within-match patterns in previous literature vary from 45-min (e.g., Bangsbo, 1994b; Carling & Dupont, 2011), 15-min (Bradley et al., 2009; Bradley et al., 2010; Akenhead et al., 2013), 5-min (Bradley et al., 2009; Carling & Dupont, 2011), and various rolling average periods of 1 – 10-min (Varley, Elias, & Aughey, 2012; Delaney et al., 2018a; Fransson, Krustrup, & Mohr, 2017; Martín-García et al., 2018a). The consensus in the literature is that activity profiles decline at three distinct phases during matches: (a) in the second half compared to the first (Figure 2); (b) after short term intense periods in both halves; and (c) in the final period at the end of each half (Carling et al., 2008). Furthermore, most (Rampinini et al., 2008; Rampinini et al., 2009a; Russell, Rees, & Kingsley, 2013) but not all (Carling & Dupont, 2011) studies have shown that these declines in physical performance are synonymous with declines in technical or skill-related performance. Therefore, it is plausible to suggest that resistance to fatigue is a key factor in the effectiveness of the ability of a player to maintain the necessary actions required to influence the game outcome in soccer (Stone & Oliver, 2009).

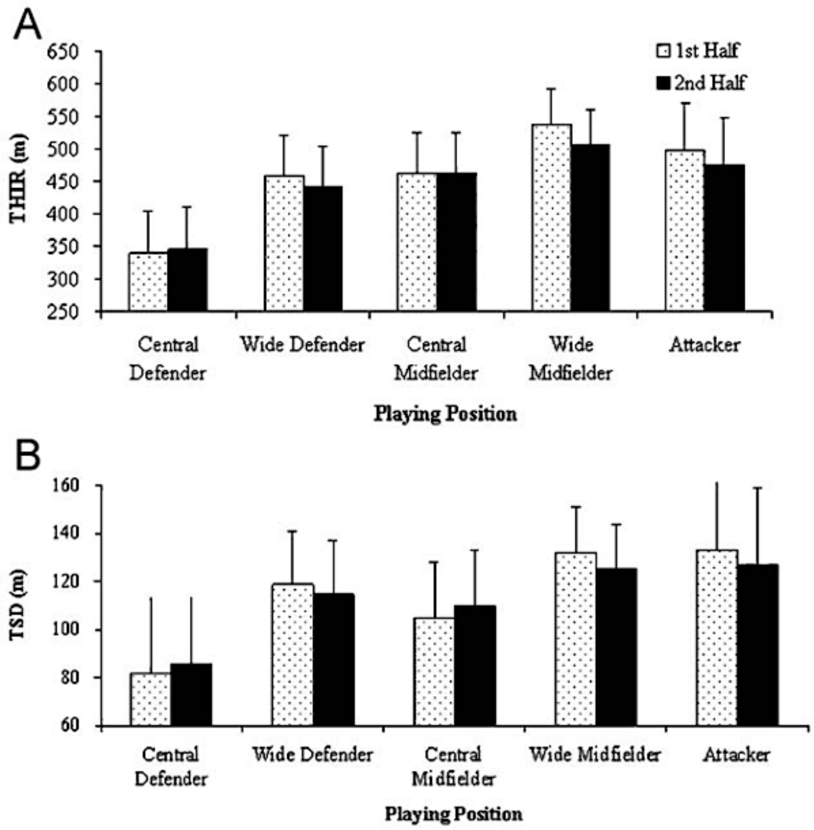

Figure 2 (A & B). Influence of player position on first and second half (A) total high-speed running (HSR) distance (19.8 – 25.2 km·h^{-1}), and (B) total sprint distance (TSD; ≥25.2 km·h^{-1}). Reproduced from Di Salvo et al. (2009).

Analysis of multiple studies in various leagues demonstrates that total distance declines by an average of 3.5 ± 1.9% in the second half compared to the first (Carling, 2013). Similar reductions in HSR (>19.8 km·h^{-1}; -2.8%) and sprinting (>25.2 km·h^{-1}; -1.8%) distances have been observed between halves in EPL players representing multiple teams and over several seasons (Figure 2; Di Salvo et al., 2009). However, these declines seem to be position dependent, with positions that typically perform more sprinting distance (i.e., FB, WM & FW) declining whereas the outputs from CB and CM players were stable or increased (Figure 2; Di Salvo et al., 2009). Furthermore, total distance and HSR has been reported to be 7.5% and 13% higher, respectively, in the first 15-min period compared to the last 15-min period in French first division players (Carling & Dupont, 2011). This is supported by data from Bradley et al. (2009) in EPL players, who reported a significant decrease in sprinting distance in the final 15-min of first half (i.e., 30 – 45-min; 34 ± 23 m; -21%) and the second half (i.e., 75 – 90 min; 36m ± 20 m; -17%), in comparison to the initial 15-min of the game (0 – 15-min; 43 ± 17 m). This pattern aligns with accelerometry measures (Barrett et al., 2016) and the number of efforts (Russell et al., 2014) and distances covered (Akenhead et al., 2013) at various acceleration and deceleration intensities. However, there are potential limitations in using the opening stages of the match as a benchmark for the subsequent periods. These may be related to the influence of self-pacing strategies (Edwards & Noakes, 2009), or factors specific to the first 15-min of play such as residual ergogenic effects from the warm-up (Russell, Rees, & Kingsley, 2013) and a desire of each team attempting to impose their style of play or gain tactical superiority over the opposition (Carling et al., 2008). Nevertheless, the declines in running intensity seen at the end of both halves are synonymous with increases in injury rates in large samples of professional adult males (Ekstrand, Hagglund, & Walden, 2011; Figure 3A) and elite youth players (Price et al., 2004; Figure 3B). Therefore, the increased injury rate in these periods has been suggested to be a consequence of impaired neuromuscular performance and loss of motor control towards the end of each half (Ekstrand, Hagglund, & Walden, 2011). This is supported by multiple studies that have reported immediate post-match reductions in markers of physical performance, such as RSA (Krustrup et al., 2006; Stone et al., 2011), single sprint performance (Rampinini et al., 2011; Lovell et al., 2003), vertical jump height (JH) (Lovell et al., 2013), and maximal strength (Rampinini et al., 2011; Brownstein et al., 2017). The mechanisms of match-related fatigue are likely to be multifaceted in origin, with several central and peripheral mechanisms implicated (see section 2.5 for detailed review).

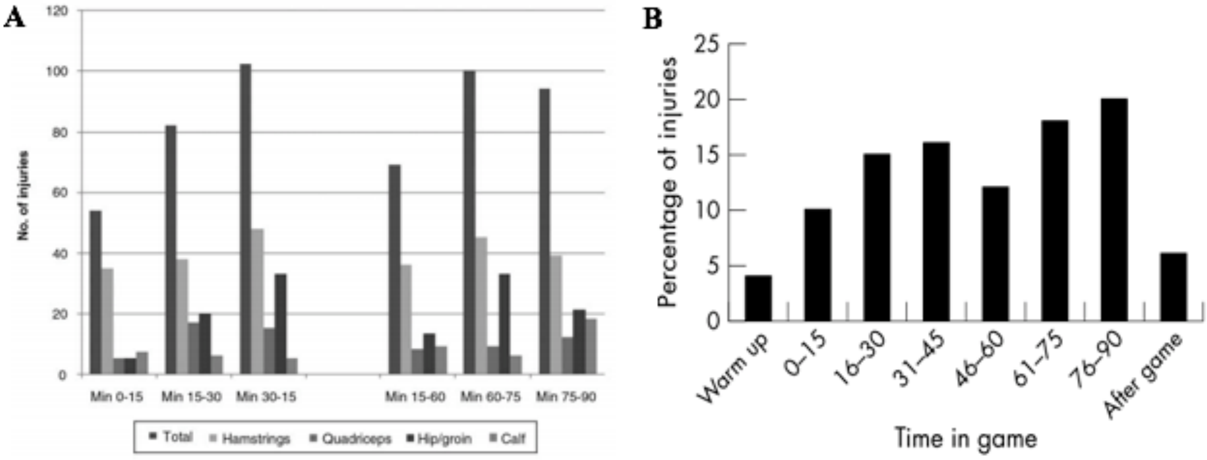

Figure 3 (A & B). The number (**A**) and percentage (**B**) of match injuries occurring within 15-minute time periods in professional adult males (**A**; Ekstrand, Hagglund, & Walden, 2011) and elite youth soccer players (**B**; Price et al., 2004).

With regards to transient fatigue during matches, the amount of HSR in the 5-min period immediately after the peak 5-min period of play has been reported to decline between 6 – 12% when compared to the average across the whole match (Mohr et al., 2003; Bradley et al., 2009). This is supported by Akenhead and colleagues (2013), who reported that in the 5-min period after the peak 5-min period, the distance covered during high-intensity acceleration (>3 $m \cdot s^{-2}$) and deceleration (<3 $m \cdot s^{-2}$) activities declined by 10.4% and 11.4%, respectively, when compared to the match average. By 10-min post the peak period, these values were similar to the match average (Akenhead et al., 2013). However, Varley, Elias, and Aughey (2012) demonstrated that pre-defined 5-min periods underestimated HSR by up to 25% and overestimated the following epoch by up to 32% when compared to rolling periods. Combined, this resulted in up to a 52% greater reduction in running performance when using rolling periods vs pre-defined periods (Varley, Elias, & Aughey, 2012). In support of this, more recent work in EPL players by Fransson and co-workers (2017), reported significant decrements in HSR across all positions in the 5-min period following the rolling peak 1-, 2- and 5-min period. Explanations for these temporary reductions are usually associated with peripheral mechanisms, with various perturbations in muscle metabolites and ion concentrations (e.g., PCr, H^+, calcium ions [Ca^{2+}], sodium ions [Na^+], potassium ions [K^+]) that impair excitation-contraction (E-C) coupling being implicated (Mohr, Krustrup, & Bangsbo, 2005; Mohr et al., 2016b; Hostrop & Bangsbo, 2017).

There is a large body of research indicating that ~72 – 96 hours of recovery is required to establish a full recovery following matches. Whilst previous reviews have summarised these responses in detail (e.g., Nedelec et al., 2012; Silva et al., 2018), physical performance (e.g., sprint times, jump performance, strength measures), physiological (e.g., muscle damage, inflammatory, immunological) and perceptual (e.g., muscle soreness, fatigue) markers have all been shown to be significantly altered until up to ~72 – 96 hours post-match (Nedelec et al., 2012; Silva et al., 2018). Several intrinsic (e.g., aerobic fitness, strength levels, age, training history, playing position) and extrinsic factors (e.g., competition level, opposition standard, number of recovery days from the previous match) likely influence the external and internal load experienced by each player with a consequent impact on the time course of recovery (Paul, Bradley, & Nassis, 2015; Silva et al., 2018). Monitoring the declines in performance and time course of recovery is of great interest to those involved in soccer for several reasons. Firstly, it can inform appropriate recovery modalities (e.g., cooling or heating strategies) and nutritional intake (e.g., glycogen repletion, branched-chain amino acids [BCAA]) to optimise recovery in this post-match window. Secondly, it can inform training practices (e.g., modality, volume, and intensity) in the days that follow the match, as exposure to high inappropriate loads in this window may be harmful. Finally, it justifies the need for well-designed training programs that achieve the desired adaptations (e.g., strength, aerobic, and anaerobic), and expose players to the necessary physical demands at appropriate timeframes during the training program to prepare them for the demands of competition.

2.2.7 Psychological demands

With much focus on the physical, physiological, and technical demands of soccer, the psychological component has often been overlooked. As discussed previously, numerous time-motion analysis studies have revealed reductions in physical activity as the match progresses, and these changes are mostly attributed to physiological mechanisms (e.g., cardiorespiratory, metabolic, and neuromuscular) (Mohr, Krustrup, & Bangsbo, 2005). However, the perceptual-cognitive demands of soccer are also challenging (Walsh, 2014; Smith et al., 2018). Players are required to process a large amount of information regarding their dynamic playing environment and execute an appropriate response depending on several factors (e.g., tactical approach, technical ability, physical capacity, game status), all whilst under pressure from opposition players and crowds (Nedelec et al., 2012). Competition at the elite level and a congested fixture schedule may further intensify these demands (Coutts, 2016). The persistence of cognitively demanding tasks may lead to mental fatigue, which is characterised as a psychobiological state in which feelings of tiredness and lack of energy occur (Boksem, Meijman, & Lorist, 2005). Mental fatigue is associated with increases in cerebral adenosine and perception of effort, as well as decreases in dopamine, motivation, attentional focus, cognitive performance, and reaction time (Boksem, Meijman, & Lorist, 2005; Martin et al., 2018; Russell et al., 2019). Soccer players will likely experience mental fatigue during training and competition, which could contribute to impairments in physical, technical, and tactical performance (Smith et al., 2018).

The negative impact of mental fatigue on endurance performance has been well-established and is attributed to a higher perception of effort (Van Cutsem et al., 2017; Martin et al., 2018). There is also evidence that mental fatigue may impair intermittent exercise performance which may have implications for soccer performance. For example, Smith, Marcora and Coutts (2015) used a self-paced 45-min non-motorised treadmill protocol designed to simulate team sport activity. In a randomised-counterbalanced order, 10 male team sport players performed the identical running protocol immediately after two 90-min interventions, consisting of either an emotionally neutral documentary (control) or the AX-continuous performance task (mental fatigue). The overall running velocity was lower after the mentally fatiguing protocol compared to the control, despite the rating of perceived exertion (RPE) being similar between protocols. These findings were confirmed in 12 recreational soccer players using a maximal intermittent running test (Yo-Yo intermittent recovery test level 1), with players running significantly lower distances following a 30-min mentally fatiguing Stroop task in comparison to a control trial (Smith et al., 2016).

Whilst the research suggests that mental fatigue impairs intermittent physical performance in a controlled environment, the evidence for this in uncontrolled soccer activity (e.g., SSG or 11 vs 11 matches) is less clear. A pair of studies by Badin et al. (2016) and Coutinho et al. (2017) investigated the effects of mental fatigue (30-min Stroop task) on physical performance during SSGs (5 vs 5 +GKs and 6 vs 6 +GKs), with only one mentally fatigued team per SSG. Both studies reported that RPE was *likely* higher in mentally fatigued players, however, the physical activity profiles assessed using GPS (distances covered, accelerations and decelerations) were similar between conditions. A further study by Coutinho et al. (2018) mentally fatigued both teams before a SSG (5 vs 5 + GKs) and compared performance with that of a control SSG. Whilst the authors did not assess RPE in this study, they reported a *likely small* reduction in the total distance covered in the mentally fatigued SSG compared to the control, yet all other metrics were similar. These findings contrast with two studies by Kunrath et al. (2018 & 2020) who reported significant increases in the total distance covered during mentally fatigued SSGs (3 vs 3 + GKs) compared to control conditions, leaving to authors to suggest a breakdown in technical actions and tactical activity resulted in the need for covering greater distances. These findings suggest that the fatigue level of the opponent may impact the influence of mental fatigue in soccer. Furthermore, it may be that the duration of the SSG protocols used in the above-mentioned studies (i.e., 12 – 18-min) were not long enough to for the players to experience the negative effects of mental fatigue, considering that similar research has consistently shown reductions in performance during prolonged endurance exercise (Martin et al., 2018), but not strength and power activities (Van Cutsem et al., 2017). The movement demands during SSGs are likely more dependent on contextual factors (e.g.., technical skills, tactical factors, decision making) in response to the approach of the opposition team (Coutinho et al., 2018; Smith et al., 2018).

Although physical performance is clearly important in soccer as it fundamentally underpins all other aspects of the game, the performance of technical skills is generally a better predictor of match outcome (Rampinini et al., 2009a). Research has indicated that performance of technical skills declines over the course of a match (Rampinini et al., 2008; Rampinini et al., 2009a), which again is typically associated with physiological mechanisms. Whilst successful execution of key technical skills (e.g., passing and shooting) is compromised under physical fatigue (Russell, Benton, & Kingsley, 2011), research in both controlled and applied settings has indicated that mental fatigue may also be contributing factor. Decrements in passing (Smith et al., 2016) and shooting (Smith et al., 2017) accuracy have been reported in technical performance tests when preceded by a mentally fatiguing 30-min Stroop task. The simulated tasks used here were the Loughborough soccer passing and shooting tests, which have been shown to have acceptable test-retest reliability and can discriminate between playing levels in soccer (Le Moal et al., 2014). However, it has been shown that these tests have impractical criterion validity when compared against actual match performance when assessed by video analysis (Serpiello et al., 2016). Nevertheless, Badin et al. (2016) assessed the effects of mental fatigue during 5 vs 5 SSGs and found reduced passing accuracy, number of positive possessions, successful tackles, and ball control capability. Taken together, the evidence suggests mental fatigue may impair technical performance during soccer-specific tasks, although again, this is unconfirmed 11 vs 11 match-play.

There is further evidence that mental fatigue can influence tactical behaviours and impair perceptual-cognitive performance in soccer players. Under controlled conditions in 12 well-trained players, Smith et al. (2016) reported a decrease in speed and accuracy of decisions in a soccer-specific film-based task following a 30-min Stroop task, compared to a control treatment. In applied settings, Coutinho et al. (2017 & 2018) reported that during SSGs, mentally fatigued teams spend less time in laterally and longitudinally synchronised positions, which suggests a breakdown in tactical behaviour. Furthermore, Kunrith et al. (2018 & 2020) reported decreases in 'tactical action quality' during 3 vs 3 +GKs SSGs under mentally fatigued conditions. Unlike the research into the impact of mental fatigue on physical and technical parameters, Gantois et al. (2020) assessed the effects of mental fatigue (30-min Stroop task) during 11 vs 11 practise matches. The authors reported that the mentally fatiguing condition impaired passing decision-making ability compared to the control.

Collectively, the research suggests that mental fatigue may impair physical, technical, and tactical performance in soccer. However, evidence for this during 11 vs 11 match-play is scarce, and there are obvious difficulties in exploring this relationship during competitive games given that it may alter performance and match outcome. Furthermore, most prior research in this area has examined the effects of artificially generated mental fatiguing protocols (i.e., video or paper-based tasks) on simulated soccer exercises or SSGs. Whilst these protocols aim to replicate match demands, there are limitations in using simulations and generalising to other exercises, which can be easily seen in the duration of the exercises (e.g., 90-min of match-play vs 12 – 18-min of SSGs). Similarly, there is limited evidence that soccer match-play induces mental fatigue and results in reduced performance in elite players, as most of the existing literature has recruited recreational or youth players. Whilst the demands of elite-level competition very likely place a greater cognitive demand on players, Martin et al. (2016) have shown that professional cyclists are more resistant to mental fatigue than those of lower-level, which is likely due to their familiarity with the conditions (Martin et al., 2016). In support of this, Marcora et al. (2015) reported that training for 12 weeks under mentally fatigued conditions improved performance by reducing time to exhaustion and RPE during a maximal cycling test in 40 healthy males, in comparison to a control training trial. This may have implications for soccer training, as this training approach could be used to enhance fatigue resistance in the latter stages of games, potentially improving physical, technical, and tactical performance.

2.2.8 Whole-season demands

A combination of domestic, continental, and international leagues and cups in elite soccer result in many fixtures throughout a season, with some elite players competing in up to 60 competitive matches (Nedelec et al., 2012). These matches will often occur within 3 days of each other, despite an abundance of research demonstrating that at least 72 hours of recovery is necessary to restore baseline physical capabilities (Nedelec et al., 2012; Silva et al., 2017). Therefore, when schedules are congested and sufficient squad rotation is not implemented, it is very likely that players are not establishing a complete recovery between matches. This is a likely reason as to why injury rates have been shown to be higher during periods of congested fixtures (Dupont et al, 2010; Dellal et al., 2015), despite no evidence of decreased locomotor activity (Carling, Gall, & Reilly, 2010; Dellal et al., 2015). For example, Dupont et al. (2010) reported the injury rate was ~6 times higher in players who regularly competed in two matches per week in comparison to one. There is evidence that fixture congestion also reduces performance. Ekstrand and colleagues (2004) reported that athletes who were subjectively perceived as underperforming at the World Cup in 2002 had played an average of ~12.5 matches in the 10 weeks before the tournament. Conversely, players who had exceeded their performance expectations had played ~9 matches in the same timeframe. These findings reinforce the need to implement effective strength, conditioning, monitoring, and recovery strategies in pursuit of optimised performance throughout the full duration of a competitive season. Additionally, this highlights the need to understand the physical demands and the consequent responses of all the activities soccer players will engage in during their training programs.

2.2.9 Summary of the demands of soccer

From reviewing the literature on the demands of soccer, it is clear that successful performance requires the development and maintenance of multiple physical and psychomotor qualities under limited time constraints due to the high fixture demands. Players must have well developed aerobic systems in conjunction with anaerobic qualities that often determine the outcome of games. These energy systems support the intermittent nature of the game, which requires repeated bouts of high-intensity activity that are underpinned by strength and power qualities, as well as technical proficiency and perceptual-cognitive skills. In addition, players must be athletic and robust enough to cope with the demands throughout the season to maintain performance and reduce the risk of injury. This requires concurrent training methods to target the multiple physical adaptations. However, limited research exists on how to best schedule each training session into the training week to optimise the required adaptations. The next section will review soccer training, with a primary focus on SSGs as they are a very popular training method and often thought to simultaneously target the multiple match demands highlighted within the first sections of this review.

2.3 SOCCER TRAINING

Due to the multifaceted match demands highlighted in the opening section of this review, soccer players are required to concurrently train multiple physical qualities aligned to successful performance, including but not limited to; aerobic capacity, RSA, agility, COD, strength, power, speed, acceleration, as well as engage with technical and tactical training. On the field, some teams may aim to develop these qualities simultaneously through training exercises involving the ball, whilst others may perform isolated physical sessions such as running drills, or a combination of both (Dupont, Akakpo & Berthoin, 2004; Fransson et al., 2018; Sarmento et al., 2018). There are multiple ways to structure soccer training and the content will ultimately depend on factors such as the club and coaching staff philosophy, the individual needs of the players, the fixture schedule, and the period of the season (Morgans et al., 2014; Walker & Hawkins, 2017). Nevertheless, it is necessary for those responsible for designing soccer training to have a detailed understanding of the demands and responses to each training session a player performs to recognise when to prescribe appropriate exercises and training loads.

2.3.1 Periodisation

Periodisation is defined as a theoretical model that offers a framework for the planned and systematic variation of training parameters in order to direct adaptations towards a training goal (Brown & Greenwood, 2005; Gamble, 2006). Variation in prescribed training exercises, volumes and intensities is a fundamental concept in any successful training program (Morgans et al., 2014). Accordingly, numerous studies have reported that periodised training results in enhanced adaptations compared to training with a constant load throughout the study period (Gamble, 2006; Williams et al., 2017). This is a consequence of prolonged exposure to the same training stimuli failing to elicit further adaptation (Gamble, 2006; Morgans et al., 2014). Additionally, sustained training loads of the same stimulus, especially when high, can lead to maladaptation and negative outcomes such as chronic fatigue and overuse injury (Gamble, 2006; Morgans et al., 2014). Either or both outcomes would result in ineffective training programs and reduce their benefit to the athlete and the team.

Traditionally, models of periodisation were designed to support the training process in sports where there is a clear intention to ‘peak’ for a major competition or tournament, such as the

Olympics in track and field or competition in martial arts (Issurin, 2010). However, in most team sports in general, and certainly soccer, athletes attempt to physically peak for ~40 – 50 fixtures that occur over ~10 – 11 months (Morgans et al., 2014). Therefore, applying traditional models of periodisation (e.g., linear, block, conjugate), particularly during the in-season phase is problematic for several reasons (Issurin, 2010; Gamble, 2006; Turner & Stewart, 2014; Morgans et al., 2014; Walker & Hawkins, 2017). Challenges of applying such models in team sport include:

- The frequency of fixtures making it difficult to find sufficient time to apply meaningful concentrated loading and tapering periods (Issurin, 2010).
- The length of the competitive season making it impossible to 'peak' over such an extended period (Issurin, 2010).
- The short pre-season, which can be less than six weeks in elite soccer (Mujika et al., 2018).
- Multiple training goals (e.g., hypertrophy, maximum strength, explosive power, metabolic conditioning, agility, acceleration, and speed) that may vary between individuals and require conflicting physiological responses (Gamble, 2006).
- Time constraints imposed by technical and tactical training (Gamble, 2006).
- Uncontrolled and unplanned external load from training and games.
- Varying individual responses to different training sessions or models (Walker & Hawkins, 2017).

More recently, the concept of strategic periodisation has become popular in some sports such as Australian rules football (AFL) and rugby codes. This is a strategy whereby teams manipulate their training in order to intentionally peak for matches or periods of perceived high importance or difficulty (Robertson & Joyce, 2018). However, in soccer, an analysis of the EPL over a decade (2006 – 2016) revealed that the winners lost on average only 4.6 times per season (Walker & Hawkins, 2017). This concept is also true for teams competing at the bottom of the league table, as in theory, every match and point gained is of very high importance to avoid the possibility of relegation. Thus, intentionally competing in some matches in sub-optimal conditions may be a risky strategy to employ for soccer coaches (Walker & Hawkins, 2017).

Nevertheless, concepts from traditional models can and should be applied where possible in soccer. Common terminology referring to different phases of training, such as macrocycles (normally referring to annual or seasonal training cycle), mesocycles (normally referring to a training block of ~4 – 6 weeks) and microcycles (normally referring to a training period of ~1-week) have been used interchangeably with terms such as 'off-season', 'pre-season' and 'in-season' in team-sport literature (Issurin, 2010). Basic principles such as progressive overload, concentrated loading blocks (particularly in the pre-season), and tapering periods can be applied in an attempt to provide sufficient stimulus for adaptation and adequate recovery for competition. Within soccer, the long-playing season along with its high number of fixtures frequently leads to detrimental consequences, such as pronounced catabolic responses (Carli et al., 1982; Kraemer et al., 2004b) and a high incidence of injuries (Gamble, 2006). Therefore, rationally periodised training plans are imperative to mitigate these responses. More specifically, reasonably structured training that avoids conflicting physiological responses, whilst facilitating the maintenance or development of the physical characteristics required for the sport (Issurin, 2010).

With regards to the in-season period in soccer, it is generally suggested that non-linear undulating periodisation models are best suited (Gamble, 2006, Turner & Stewart, 2014). This approach varies training prescription (e.g., physiological target, volumes, and intensities) on a session-by-session basis to account for multiple training goals (Gamble, 2006; Turner & Stewart, 2014). One of the benefits of this system is that it can be easily adapted to respond to variable fixture schedules and external factors, such as success in knock-out competitions, travel demands and variability in physical stimuli (Turner & Stewart, 2014). During a typical microcycle where there is one match per week, most professional teams will perform ~4 – 5 field-based training sessions and ~1– 2 resistance training sessions (Bangsbo, Mohr, & Krustrup, 2006; Owen et al., 2017a; Martín-García et al., 2018b; Cross et al., 2019). Furthermore, there is the possibility that some teams or players will perform additional training (e.g., mobility, recovery, proprioception, individual work) interspersed around these main team sessions.

Various soccer microcycle structures have been proposed in previous literature (Akenhead et al., 2016; Owen et al., 2017a; Walker & Hawkins, 2017; Martín-García et al., 2018b), yet there is limited evidence to support their effectiveness. Nevertheless, a weekly structure of a recovery period from the previous match (~1 – 2 days), followed by a concentrated loading phase ~1 –

2 days), and finally, a taper (~1 – 2 days) leading into match-day (MD) is typically applied. This can be seen in several studies (Impellizzeri et al., 2004; Owen & Wong, 2009; Malone et al., 2015a; Owen et al., 2017a; Oliveira et al., 2019b), whereby the volume of work during the MD-1 is reduced in comparison to the days where there is a conditioning emphasis (e.g., MD-4 and MD-3). Over a longer period (i.e., macrocycles and mesocycles), previous work in soccer has shown that there is limited variation across a season (Malone et al., 2015a; Los Arcos et al., 2017; Oliveira et al., 2019a), though some studies do report that total training volume is higher in the first phase of the season compared to the last (Los Arcos et al., 2017; Mara et al., 2015).

The existing literature in this area is descriptive of the specific team studied, so may be limited in its application to a broader number of teams when considering the different schedules and philosophies across clubs. Furthermore, the influence of individual responses should not be overlooked. For example, some athletes may respond favourably to a certain training stimulus (i.e., perform, recover, and adapt rapidly) in comparison to others. Several factors are likely to influence this response, such as player age and training history, physical characteristics (e.g., strength and aerobic capacity), previous injuries, lifestyle (e.g., sleep, nutrition, hydration) and muscle fibre characteristics (i.e., type I vs type II) (Morgans et al., 2014). Furthermore, training and match loads are very likely to fluctuate significantly between athletes, depending on motivation, work rate, match playing time and playing position differences. Therefore, the ability to monitor both the dose (i.e., physical and physiological load) and the response (i.e., fatigue, recovery and adaptation) is imperative in team sports such as soccer. This can be a challenge when considering the number of athletes in a squad (~25 – 30) and the previously mentioned time constraints. Therefore, the identification of valid, reliable, and practical monitoring methods is imperative, which will be reviewed in sections 2.4 and 2.7. What is clear, is that teams are likely to be targeting numerous and possibly competing physiological adaptations (e.g., aerobic capacity and strength) within a microcycle (Turner & Stewart, 2014; Walker & Hawkins, 2017). Consequently, there is a need to evaluate how these differing training sessions interact with each other, and how this may influence their sequencing or placement within the microcycle. Furthermore, the use of training modalities that can simultaneously target multiple physiological adaptions in combination with the technical and tactical requirements of the game may be beneficial. A popular training method that is thought to accomplish this is SSGs, which will be reviewed over the following sections.

2.3.2 Small-sided games

A small-sided game (SSG) is an umbrella term that describes any smaller format of match-play, characterised by either a reduction in player numbers and/ or a reduction in pitch dimensions (Hill-Haas et a., 2011). In high-performance sport, it is generally accepted that maximum benefits are achieved when the training stimuli are similar to, or above the competition demands (Bompa, 1983). As discussed in section 2.2 of this review, a characteristic of high match performance is that players possess the ability to perform high-intensity actions whilst limiting fatigue, therefore well-developed aerobic and anaerobic qualities are required (Köklü et al., 2015). Typically, SSGs are performed in several repetitions interspersed by a set recovery period, and therefore, could be considered as a mode of HIIT. It is well established that HIIT, when programmed with appropriate volumes and intensities, allows for the simultaneous development of aerobic and anaerobic energy systems (Dellal et al., 2010a; Billat, Hamard, & Koralsztein, 2002). Therefore, a popular topic in SSG research is to compare the responses between SSGs and traditional running-based modes of interval training, which is discussed in section 2.3.2.1. As previously mentioned, the ability of one training method to fulfil a broad range of requirements is appealing. Indeed, SSGs are a training method which are primarily used to replicate the specific physical and physiological demands of soccer, whilst simultaneously working with the ball and maintaining interactions between team-mates and the opposition (Reilly & White, 2004; Hill-Haas et al., 2011; Aguiar et al., 2012).

There is an abundance of research on the use of SSGs in soccer, with much focus on the responses during (i.e., within SSG) and longer-term (i.e., chronic) adaptions. Furthermore, the structural format of an SSG is a very important consideration, and in practice, is frequently modified to suit the coaching aims or the number of players involved in a training session (Casamichana, Bradley, & Castellano, 2018). Numerous factors can be manipulated during SSGs, which are summarised in Figure 4. Manipulation of these variables has drawn focus in previous research, as this has been shown to influence the demands, and therefore the physiological responses and adaptations (Casamichana & Castellano, 2010; Aguiar et al., 2012). Nevertheless, comparing different formats of SSGs can be an arduous task since many variables can be manipulated (Figure 4), and there is inconsistency amongst the methods (e.g., work-rest durations, participant characteristics, task constraints, structural format) in previous literature (Dellal et al., 2011a; Clemente et al., 2014a; Casamichana et al., 2015). For this reason, caution should be applied when comparing between studies and drawing definitive conclusions from the literature. Nevertheless, there are some areas where consistent findings have been reported, and useful practical inferences can be made. The key literature related to SSG training, and the most prevalent topics will be discussed over the following sections.

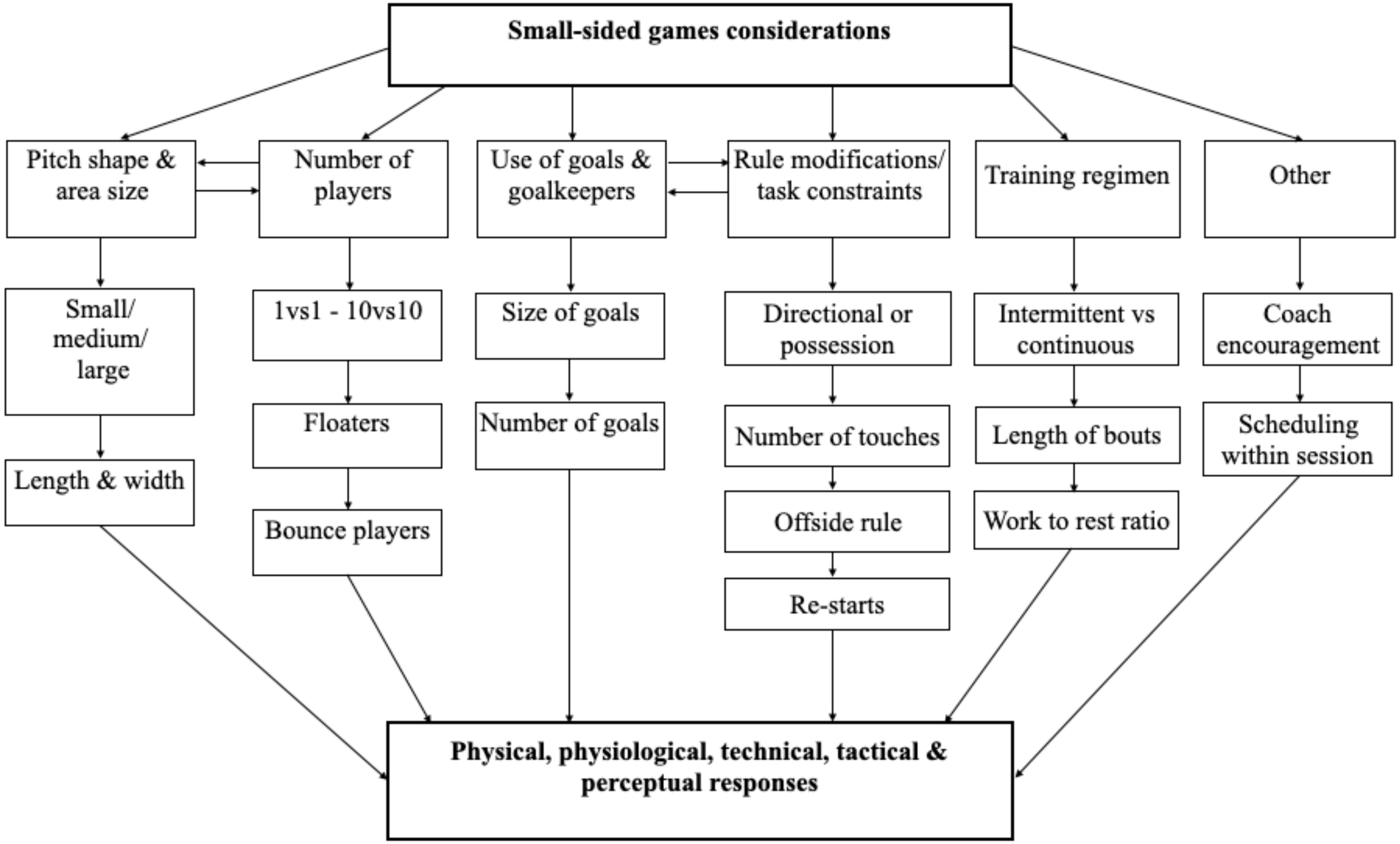

Figure 4. Summary of the factors to consider when prescribing small-sided games.

2.3.2.1 Comparisons to running-based interval training

When assessing the effectiveness of SSGs as a training tool, many previous studies have compared the acute and chronic responses of SSGs in comparison to running-based modes of interval training. Regarding the definition of these running-based training sessions, there is a broad range of formats chosen with variations in speed, distances, and work-rest periods. These training modalities have been given several terminologies across the literature (e.g., HIIT, generic training, aerobic training, repeated sprint training, interval training). For the sake of this review, these have been grouped into the term ‘interval training’, which will cover the expansive range of methods chosen. Typically, the responses are determined either during or immediately post-training, with physiological markers (e.g., BLa, HR), external demands (e.g., GPS), and perceptual scales (e.g., RPE). Additionally, numerous studies have measured changes in physical performance markers after a set training period (i.e., chronic adaptations). Many of these interventions are performed in addition to players normal technical and tactical training, which is likely due to the logistical issues associated with altering the training schedule of a competitive team. Furthermore, many different SSG protocols and variables have been assessed. Both factors should be considered when making inferences from the literature.

With regards to the acute perceptual and physiological responses, Sassi, Reilly and Impellizzeri (2004) investigated the responses to four formats of SSG (i.e., 4 vs 4 with and without GKs; 8 vs 8 'free touch' and ‘pressing’ based) in comparison to interval running. The SSGs were performed in 4 bouts of 4-min with 150 s of recovery, and similarly, the interval running protocol consisted of 4 bouts of 1 km repeats with the same recovery period. The authors reported that the 4 vs 4 SSG formats elicited a greater HR response (SSGs, 91 $\%HR_{max}$; intervals, 85 % HR_{max}) and similar BLa values (SSGs, 6.4 $mmol \cdot L^{-1}$; intervals, 7.9 $mmol \cdot L^{-1}$) compared to the interval running group (Table 2). However, this study was performed before the widespread use of GPS in team sport, hence no information was collected concerning the external demands of the SSGs. Similarly, Dellal et al. (2008) assessed the average percentage of heart rate reserve (%HRR) in various SSG formats compared to high-intensity interval running drills. The duration of work and rest periods varied for each training protocol (Table 2), and the speeds prescribed for the intermittent runs were based on the maximal aerobic speed (MAS) of each player. The authors reported that the SSGs (i.e., 1 vs 1; 2 vs 2; 4 vs 4 +GKs; 8 vs 8; 8 vs 8 +GKs; 10 vs 10 +GKs) induced similar %HRR to some of the interval formats (i.e., 15 s at 110% MAS with 15 s rest; 30 s at 100% MAS with 30 s rest; 5s at 120% MAS with 2

5s rest). However, it should be noted that out of all SSG formats performed, the 2 vs 2 and the 8 vs 8 +GKs formats elicited the highest %HRR, however, this response was still lower than some of the interval protocols assessed (i.e., 10 s at 110% MAS with 10 s rest; 30 s at 100% MAS with 30 s active recovery at 9 km·h^{-1}) (Table 2). Another key finding from this study was that the %HRR in the interval protocols were more homogeneous than the SSGs, with lower CV values reported (intervals, 4.5 – 8.5%; SSGs, 8.8 – 13.4%). This is unsurprising as one of the benefits of interval training over SSGs is that it is easier to control the exercise intensity and work rate of the players. A limitation of this study was that due to the subjects being elite players in full-time training, there was no randomisation of the order of SSGs and the intermittent runs performed. Therefore, possible day-to-day HR variability of the players may have influenced the results. Furthermore, external loads or perceptual responses (e.g., GPS or RPE) were not recorded, which may aid our understanding of the movement patterns driving the physiological responses. A pair of more recent studies examined both the physiological and psychological responses in professional adult (Selmi et al., 2018) and youth players (Selmi et al., 2020). Both studies used broadly similar methods, with 4 vs 4 SSGs (25 x 35 m pitch size) compared with interval training (15 s at 110% MAS with 15 s rest), and protocols were performed in 4 bouts of 4-min with 3-min of passive recovery. Both studies reported similar physiological responses (HR, RPE & BLa) between SSGs and intervals. Yet, a negative mood disturbance was observed after the interval running in both the professional (assessed by the profile of mood state [POMS]) and the youth players (assessed by a Physical Activity Enjoyment Scale). Collectively, these studies demonstrate that some formats of SSG training can elicit similar internal physiological responses to both long duration (e.g., Sassi et al., 2004) and short duration (e.g., Dellal et al., 2008) interval training. Furthermore, during SSGs, these physiological responses are provoked whilst maintaining the enjoyment and mood stability of the players (Selmi et al., 2018; Selmi et al., 2020), which may be beneficial over a season. However, it is very likely that this is dependent on the format of SSG chosen, so the factors highlighted in Figure 4 should be understood and manipulated to target the required responses. Additionally, no data on the external loads of the SSGs were provided in the above studies mentioned, which could impact the fatigue and recovery responses of the players.

Table 2. Summary of key studies that have assessed the acute and chronic responses of various SSG protocols in comparison to interval training.

Study	Participants/ design	SSG format	Interval format	Acute response	Chronic adaptations	Conclusions
Reilly & White (2004)	18 elite male youth players from an EPL club (age 18.2±1.4) randomly assigned to either SSG or interval group in addition normal training.	- 6 x 4-min with 3-min active recovery (jogging at 50-60% HR_{max}). - 2 x per week for 6 weeks.	- 6 x 4-min running at 85-90% HR_{max} with 3-min active recovery (jogging at 50-60% HR_{max}). - Performed 2 x per week for 6 weeks.	- BLa similar between groups for all sessions (11.7 – 13.5 mmol·L^{-1}).	- CMJ, SJ, estimated VO_{2max}, 10-30m sprints, agility, anaerobic capacity (repeat 30 s shuttle test) all similar between groups at the end of the 6-week training block.	- SSGs are as effective as interval training for in-season maintenance of anaerobic and aerobic fitness.
Sassi, Reilly, & Impellizzeri (2004)	11 elite Spanish male first division players performed each training session once.	- Each format (A – D) performed once. - 4 x 4-min with 150 s recovery. - (**A**) 4vs4 - (**B**) 4vs4+GK - (**C**) 8vs8 free touch - (**D**) 8vs8 'pressing'	- 4 x 1 km repeats with 150 s of recovery	- Average HR (bpm) & BLa (mmol·L^{-1}) reported. - SSGs: (**A**) 178±4bpm; 6.4±2.7mmol·L^{-1} (**B**) 174±7 bpm, 6.2±1.4mmol·L^{-1} (**C**) 160±3bpm, 3.3±1.2mmol·L^{-1} (**D**) 175±4 bpm, BLa NR. - Intervals: - 167±4 bpm, 7.9±3.4 mmol·L^{-1}.	- NR.	- With the exception of SSG (C), all formats induced similar or higher HR responses to extensive interval running. - Both formats of 4vs4 (A&B) produced similar BLa values to interval running.
Impellizzeri et al. (2006)	40 elite male youth players (age 17±1) split into 2 groups of 20 (SSG or interval group). Performed SSG or intervals 2 x per week on top of normal training.	- 3vs3+GK, 4vs4+GK, 5vs5+GK. - 4x4-min, 3-min rest. - 2 x per week for 12 weeks.	- 4 x 4-min running at 90-95% HR_{max}, 3-min recovery. - 2 x per week for 12 weeks.	- SSG average; %HR_{max} 90.7 ± 1.2%. -Interval average; %HR_{max} 91.2 ± 2.2%. - Similar sRPE for both groups.	- Similar increases in VO_{2max} (+ 7-8%), LT (+ 9-10%), RE at LT (+ 3%) after both SSG & interval training. - Similar increases in performance in soccer specific endurance test (+14-16%). - Increased match physical outputs (TD + 4-6%; HSR [>14 km·h^{-1}] + 23-25%).	- SSG as effective as intervals in developing develop aerobic fitness and soccer performance. - SSG may be advantageous due to ability to concurrently train technical & tactical aspects.
Dellal et al. (2008)	- 10 elite French male first division players (age 26±3) performed both SSG & interval training 1 x per week as part of normal training. - %HRR observed for each drill.	- Each protocol (**A** – **F**) performed once over 8-week period: (**A**) 1vs1 (4x90s / 90s rest); (**B**) 2vs2 (6x150s / 150s rest); (**C**) 4vs4+GK (2 x 4-min/ 3-min rest); (**D**) 8vs8+GK (2 x 10-min/ 5-min rest); (**E**) 8vs8 (4 x 4-min/ 3-min rest); (**F**) 10vs10+GK (3 x 20-min/ 5-min rest).	- Each protocol (**G** – **K**) performed once over 8-week period: (**G**) 30s at 100%MAS/30s rest (2 x 10-min/ 5-min rest); (**H**) 30s at 100%MAS /30s AR at 9km·h^{-1} (2 x 10-min/ 5-min rest); (**I**) 15s at 100%MAS/15s rest (2 x 10-min/ 8-min rest); (**J**) 10s at 110%MAS /10s rest (2 x 7-min/ 6-min rest); (**K**) 5s at 120%MAS /20s rest (1 x 7-min).	- Average %HRR reported for each condition: - SSGs: (**A**)77.6±8.6;(**B**) 80.1±8.7; (**C**) 77.1±10.7; (**D**) 80.3±12.5; (**E**) 71.7±6.3, (**F**) 75.7±7.9. - Intervals: (**G**) 77.2±4.6; (**H**) 85.7±4.5; (**I**) 76.8±4; (**J**) 85.8±3.9, (**K**) 80.2±6.8.	- NR.	- Possible to use some SSG formats to induce similar %HRR to intermittent exercise. - However, intervals **H** & **J** had higher %HRR than all SSGs. - Higher variability in individual responses during SSGs compared to intervals as it is harder to control activity of players. - Choice of player number, presence of GKs, playing area and instructions affect HR responses during SSGs.

Hill-Hass et al. (2009a)	19 elite male youth players (age 14±1yr) randomly assigned to SSG (*n*=10) or interval group (*n*=10) over 7-week period alongside normal training.	- 2vs2 – 7vs7 under various conditions (coach prescribed). - Total duration 30 – 45-min. - Performed 2 x per week for 7-weeks.	- Various aerobic power, intermittent HSR, sprint training COD training and repeated-sprint training. - Total duration 30 – 45-min. - Performed 2 x per week for 7-weeks.	- Average sRPE (CR10 scale) higher for interval training group (8.2±1.0 vs 7.5±1.2 AU). - No differences in time spent in various HR zones) or weekly perceptual well-being.	- Both training groups improved YYIRTL1 performance (+ 17–22%), with no differences between groups. - No changes or differences between groups for all other performance measures (i.e., VO_{2max}, RSA, or sprint performance).	- Both SSG and running based training equally effective at improving YYIRTL1 despite higher perceived effort during running based training.
Los Arcos et al. (2015)	- 17 elite male youth players (age 15.5±0.6yr) performed either SSG (*n*= 9) or interval (*n*= 8) training for 6 weeks.	- 2vs2, 3vs3 & 4vs4 under various conditions. - All SSGs performed in 3 x 4-min bouts with 3-min rest. - Performed x 2 per week on top of normal training.	- 3 x 4-min at 90-95 $\%HR_{max}$, 3-min active recovery (jogging at 50-60 $\%HR_{max}$). - Performed x 2 per week on top of normal training.	- Non-significant or possibly small higher sRPE in interval group. - SSG spent more time at >90 $\%HR_{max}$, but less time in lower HR intensities (<90%).	- No significant differences in MAS between groups after 6-weeks. - CMJ performance similar between groups. - PACES score significantly better after SSG vs interval group.	- SSGs as effective as maintaining aerobic fitness as interval training whilst promoting high physical enjoyment.
Eniseler et al., (2017)	19 elite youth male players (age 17±1yr) performed either SSG (*n*=10) or RSA training (*n*=9) twice per week on top of their normal programs for 6-weeks.	- 3vs3+GK (18 x 30m pitch) - 4 x 3-min with 4-min recovery. - Performed 2 x per week for 6 weeks.	- 6 x 40m maximal sprints with 20s rest. - 3 sets with 4-min inter-set rest. - Set 1, straight line; set 2, 45-degree turn; set 3, 90-degree turn. - 720m total sprint volume.	- Mean $\%HR_{max}$ during SSG was 89.52±5.47%. - No markers reported for interval group.	- SSG group improved short passing ability (LSPT), RSA decrement % (6 x 20m shuttles with 20s rest), but not YYIRTL1. - RSA group did not improve LSPT, but improved RSA decrement % and YYIRTL1.	- SSG training is effective in improving RSA and technical skills simultaneously. - SSG is a time efficient method of training.
Selmi et al. (2018)	16 professional males (age 24±0.9yr) performed either SSG or interval training on separate days.	- 4vs4 possession based. - 4 x 4-min/ 3-min rest	- 15s at 110% MAS/ 15s rest - Performed in 4 blocks of 4-min with 3-min rest between.	- No difference in $\%HR_{max}$, BLa, or RPE between conditions: - SSGs: 86.8±3.7$\%HR_{max}$, 4.6± 0.7 $mmol \cdot L^{-1}$, 7±0.9 AU. - Intervals: 87±4$\%HR_{max}$, 4.7± 0.6 $mmol \cdot L^{-1}$, 7.1±1 AU. - POMS higher post intervals vs SSG.	- NR.	- SSG & intervals produce similar physiological responses. - Intervals produced mood disturbance whereas SSG did not.

Abbreviations: %HRR, percentage of heart rate reserve; YYIRTL1, Yoyo intermittent recovery test level 1; $\%HR_{max}$, percentage of maximum heart rate, sRPE; session rating of perceived exertion (duration x RPE); CR10, Borg scale of perceived exertion; RSA, repeated sprint ability; COD, change of direction; LSPT, Loughborough soccer passing test; BLa, blood lactate concentration; AR, active recovery; MAS, maximum aerobic speed; POMS, Profile of Mood States; GK, goalkeepers; LT, lactate threshold; RE, running economy; CMJ, countermovement jump; SJ, squat jump; yr, years; NR, not reported.

Numerous studies have also investigated the chronic adaptations to SSG training in comparison to various formats of interval running (Table 2; Reilly & White, 2004; Impellizzeri et al, 2006; Hill-Haas et al., 2009a; Ali, 2011; Radziminski et al., 2013; Los Arcos et al., 2015; Eniseler et al., 2017). An early study by Reilly and White (2004) recruited 18 professional youth players from an EPL club and assigned them to either SSG (5 vs 5) or an interval training group (~85 – 90% HR_{max}) over 6 weeks. Players completed the training interventions twice per week on top of their normal programs, and both protocols consisted of 6 repetitions of 4-min interspersed by 3-min of active recovery (i.e., jogging at ~50–60% HR_{max}). At the end of the 6-week training block, there were no significant differences between groups in all performance indicators measured (i.e., countermovement jump [CMJ]; squat jump [SJ]; 10 – 30 m sprint times; agility T-test; 5 x 30s anaerobic shuttle runs; multi-stage shuttle-run to estimate VO_{2max}). Furthermore, there were no significant differences in peak BLa (SSG, 12.7 – 13.5 $mmol \cdot L^{-1}$; intervals, 11.7 – 13.0 $mmol \cdot L^{-1}$) between groups over the study period. Based on these findings, the authors concluded that both SSG and intervals are effective for maintaining in-season aerobic and anaerobic fitness. Unfortunately, no markers of training load were reported in this study, and limited information on the scheduling and format of the 5 vs 5 SSG were presented (e.g., time in microcycle, pitch size, use of GKs, rules or coach encouragement). The early findings of Reilly and White (2004) are supported by a more recent meta-analysis of seven studies by Moran et al. (2019), who summarised the effects of SSGs vs 'conventional endurance training' on aerobic performance in male youth soccer players (age <18 yr). The inclusion criteria for 'conventional endurance training' in this meta-analysis was training consisting of continuous running or extensive interval training involving work durations greater than 3-min. The authors concluded that SSGs can be used instead of, or in addition to interval training for the development of aerobic capacity. To induce these benefits, the authors recommended that a minimum of 4 sets of 4-min SSG repetitions should be programmed twice per week.

From assessing the literature, it is clear that some formats of SSGs can elicit similar acute physiological responses to various modes of interval training. Consequently, over a longer period, this results in comparable outcomes in maintaining or improving markers of fitness in both elite and sub-elite players of various ages (Moran et al., 2019; Kunz et al., 2019). Furthermore, the enjoyment, as well as the technical and tactical demands the players experience during SSGs is clearly superior in comparison to intervals, which may be beneficial in maintaining the motivation and performance of players over a season (Selmi et al., 2018;

Selmi et al., 2020). However, limited information exists on the fatigue responses and recovery time course following SSG training. It is possible to theorise that the diverse movement demands during SSGs (e.g., accelerations, decelerations, changing direction, kicking, tackling, and body contact) in comparison to conventional interval training (e.g., typically straight line running), may result in significant neuromuscular and mechanical fatigue (Harper & Kiely, 2018). In particular, high-intensity accelerations and decelerations may impose distinct physiological and mechanical stresses on players (Harper, Carling, & Kiely, 2019). Firstly, the metabolic cost during acceleration is known to be greater in comparison to running at a continuous speed (di Prampero et al., 2005; Osgnach et al., 2010). In addition, decelerations involve a high force braking ground reaction component and eccentric muscle contractions (McBurnie et al., 2022), which are well known to predispose the lower limb musculature to structural damage, such as myofibrillar, cytoskeletal, and Z-line disruption (Clarkson & Sayers, 1999; Fridén & Lieber, 2001). This mechanical disruption is thought to primarily manifest as low-frequency fatigue (LFF), impairments in the E-C coupling process, and may reduce CNS function through afferent feedback (reviewed in section 2.5.2.1). Therefore, it is unsurprising that the number of high-intensity accelerations and decelerations performed during matches has been associated with post-match reductions in force production capabilities and indicators of muscle damage (de Hoyo et al., 2016; Hader et al., 2019). However, high-intensity running also involves high force repetitive eccentric muscle contractions and has been linked to muscle damage and declines in performance after matches (Thorpe & Sunderland, 2012; de Hoyo et al., 2016; Hader et al., 2019). Therefore, the velocity at which intervals are performed, and the pitch dimensions selected for the SSGs (discussed in section 2.3.2.3), are very likely to influence the degree of fatigue experienced as a result of both training methods. Furthermore, it is possible that the additional demands during SSG play, such as physical contact, jumping, kicking, and tackling may also contribute to muscle damage (Bloomfield et al., 2007; Ispirlidis et al., 2008; Nedelec et al., 2012). However, it should be noted that it is well known that unaccustomed exercise exacerbates the degree of muscle damage and soreness experienced, therefore, the training history and physical characteristics of the players are likely to have a strong impact on the degree of fatigue experienced (Owen et al., 2015; Johnston et al., 2015b).

2.3.2.2 Comparisons to match-play

Another key topic in SSG research is comparing the physical demands to full format match-play (i.e., 11 vs 11). The rationale for investigating this is clear, considering that 11 vs 11 matches are fundamentally the overarching activity coaches are trying to replicate and improve. Indeed, numerous studies have compared the demands of SSGs to 11 vs 11 matches (Table 3; Allen et al., 1998; Gabbett & Mulvey, 2008; Casamichana, Castellano, & Castagna, 2012; Dellal et al., 2012a; Castellano & Casamichana, 2013a; Hodgson, Akenhead, & Thomas, 2014; Lacome et al., 2018; Abbott, Brickley, & Smeeton, 2018; Martín-García et al., 2019). Consistent with the previous section, many studies have compared the immediate physiological and perceptual demands, but here, there is often additional information profiling the movement demands of each activity. The movement demands are typically measured using GPS and accelerometer data (see section 2.4 for review), which is valuable data that can be used when attempting to replicate or overload components of the competition demands during training.

Within this area, there is a general agreement that although most formats of SSG do not replicate the HSR demands of matches, the internal (e.g., HR, BLa) and perceptual (e.g., RPE) response is often similar or greater (Table 3). Dellal and colleagues (2012a) compared the responses of SSGs (4 vs 4, 30 x 20 m, 4 x 4-min with 3-min rest, possession-based) against 11 vs 11 friendly matches in 40 adult male international players. The authors reported that overall, the RPE was similar between SSGs and match-play (Borg CR10; 7.3 – 8.0 vs 7.4 – 8.0 AU), whilst the HR responses were greater during the SSGs (%HR_{max}; 84.7 – 87.6% vs 81.7 – 86.3%). Somewhat surprisingly in this study, the BLa values were lower immediately post the SSGs (2.8 – 3.0 vs 4.2 – 5.4 mmol·L^{-1}), and relative to total playing time, the HSR (>19.8 km·h^{-1}) was higher (483 – 639 vs 315 – 371 m) in comparison to matches. Whilst on the surface this seems contradictory, this is likely explained by the inclusion of rest periods (i.e., 3-min) between repetitions in the SSGs, allowing players to recover between bouts, thus resulting in lower BLa values and greater HSR outputs. Additionally, it should be acknowledged that inconsistent methods were used in assessing the movement demands (i.e., 5 Hz GPS for SSG vs multiple-camera system for match-play), and these techniques should not be used interchangeably (see section 2.4.2 for more detail). Indeed, the findings of Dellal et al. (2012a) conflict with the bulk of the literature, which suggests smaller format SSGs do not stimulate the HSR demands of matches (Gabbett & Mulvey, 2008; Hodgson, Akenhead, & Thomas, 2014; Casamichana, Castellano, & Castagna, 2012; Lacome et al., 2018; Abbott et al., 2018; Martín-García et al., 2019). However, as GPS technology has improved in more recent years (i.e., sampling rates >5 Hz), practitioners and researchers have the ability to quantify acceleration and deceleration activity more precisely. Consequently, it has been revealed that SSGs often result in greater acceleration and deceleration demands than match-play (Table 3).

For example, Lacome et al. (2018) compared the locomotor demands (distance, HSR, acceleration and deceleration) of four different formats of SSG (4 vs 4 +GKs, 6 vs 6 +GKs, 8 vs 8 +GKs and 10 vs 10 +GKs) against competitive matches in a squad of elite players. Unsurprisingly, only the 10 vs 10 +GKs format (102 × 67 m) permitted players to reach similar intensities for total distance and HSR covered per minute. In contrast, the 4 vs 4 +GKs (25 x 30 m) format overloaded the acceleration and acceleration demands in comparison to matches (Table 3). As discussed above, these are likely to be key movement patterns that are driving the comparable HR, BLa and RPE responses reported between SSGs and 11 vs 11 match-play.

Another key variable to consider is the accelerometry measured demands. Beenham et al. (2017) found that the summation of acceleration and deceleration in each anatomical plane (X, medial-lateral; Y, anterior-posterior; Z, caudal-cranial) (see section 2.4.5 for more detail) was significantly higher in various SSG formats (2 vs 2, 3 vs 3 and 4 vs 4) in comparison to 11 vs 11 matches (Table 3). The authors concluded that previous literature using fixed speed thresholds had underestimated the physical demands of SSGs. In addition, they suggested that SSGs produce a 'density' type of training stimulus by imposing a greater mechanical demand than match-play (Beenham et al., 2017). Again, the evidence that SSGs produce more acceleration, deceleration, and COD activity than matches is important, considering the influence these activities may have on muscle damage, and the consequential fatigue in the hours and days that follow (Nedelec et al., 2012). However, there is very limited research in this area, and the literature may benefit from investigations into the fatigue responses induced by SSGs.

Table 3. Summary of key studies that have compared the demands of SSGs to 11 vs 11 match-play.

Study	Participants/ design	SSG format	Key results	Conclusions
Hodgson, Akenhead, & Thomas (2014)	- 8 university-level male players (age 20±1 yr) performed 3 different SSG formats on 3 separate occasions. - 10 Hz GPS data compared against 18 professional matches using the same GPS system and metrics.	- 5vs5 (including GKs) - Physical and technical demands on small (30x20m), medium (40x30m) and large (50x40m) pitch sizes assessed. - 4 x 4-min with 3-min recovery.	- Distance covered accelerating and decelerating per meter of total distance higher than match play for all SSG pitch sizes: small (+10%), medium (17%), large (+14%). - Compared to small pitches, movement demands (TD, HSR, ACC & DEC) higher on medium and large SSG sizes with the same player number. - $\%HR_{max}$ similar between pitch size (small, 86%; medium & large, 87%). - Higher technical demand (shots, passes, tackles) on smaller pitches.	- The distances covered accelerating and decelerating is relatively higher during SSGs compared to matches. - Changing pitch size influences the physical and technical demands of SSGs.
Beenham et al. (2017)	- 40 well-trained male youth players (17±0.6 yr) were monitored with 5 Hz GPS devices during 2vs2 (*n*= 10), 3vs3 (*n*= 7) and 4vs4 (*n*= 5) SSGs. - 6 friendly matches also analysed.	- All games were possession based, no GKs involved and limited to 2 touches: - 2vs2, 20x15m, 4x2-min/ 3-min rest. - 3vs3 25x18m, 4x3-min/ 3-min rest. - 4vs4 30x20m, 4x4-min/ 3-min rest.	- PL per min was significantly higher than match-play during all SSGs. - 2vs2, 15.00 ± 3.53; 3vs3, 14.68 ± 3.27; 4vs4, 13.47 ± 3.35; match-play, 10.18 ± 2.12 AU.	- SSGs elicited greater external loads than matches. - Previous studies not utilizing accelerometer data may have underestimated the demands of SSGs.
Lacome et al. (2018)	- 21 elite male players (age 25±5 yr) monitored with 15 Hz GPS over 2 seasons. - Rolling average (1-15-min periods) data from various SSG formats was compared against friendly (*n*=7) and competitive (*n*=5) games.	- The most standardised formats over 2 seasons selected: (1) 4vs4+GKs, 25x30m, 6x3-min/ 90s rest; (2) 6vs6+GKs, 30x40m, 4x4-min/ 2-min rest; (3) 8vs8+GKs, 40x40m, 2x10-min/ 3-min rest; (4) 10vs10+GKs, 102x67m, 1x30-min/ no rest.	- Compared with matches, only 10vs10 SSGs allowed players to reach similar running intensities for TD and HSR. - Only 4vs4 (over 1-4 min) allowed the attainment of a moderately-to-largely greater MechW (ACC, DEC & COD) than matches. - The magnitude of the differences in locomotor intensity between SSGs and matches was highly position- and SSG- dependent, irrespective of the rolling average durations.	- Peak locomotor intensity can be modulated during SSGs of various formats and durations to either over- or underload match demands, with 4v4 placing the greatest and the least emphasis on MechW and HSR, respectively.
Abbott, Brickley, & Smeeton (2018)	- 46 EPL U-23 male players (19±1 yr) were monitored over 22 matches and 39 SSG training sessions. - RPE recorded and GPS (10 Hz) demands assessed for average and peak 1-min periods.	- SSGs grouped into small (1vs1-3vs3), medium (4v4-6vs6) and large (7vs7-10vs10) al +GKs. - Area size was $120m^2$ per player. - 4x4-min/ 3-min rest for all games.	- Distance and speed demands increase with player number and absolute playing area. - Only the large formats were able to replicate the high-intensity demands. - No SSG replicated the peak 1-min demand of competition. - Small formats had the highest moderate-intensity ACC and DEC demands. - RPE highest in the smaller format SSGs and decreased with player number.	- SSGs replicate the average but not the peak demands of competition for specific variables. - Demands vary for SSG format.
Martín-García et al. (2019)	- 21 elite male players (age 20±1 yr) monitored with 10 Hz GPS over a competitive season. - Various GPS metrics compared against the most demanding passages of play in competitive matches.	- 5vs5+GKs (33x40m, 5-min period). - 6vs6+GKs (33x40m, 5-min period). - 9vs9+GKs (72x65m, 10-min period). - 10vs10+GKs (105x65m, 10-min period).	- Distance and speed demands increase as the SSG format (player number and pitch size) increases, yet ACC and DEC demands decrease. - Smaller games (i.e., 5vs5+GKs, 6vs6+GKs) overload ACC and DEC demands in comparison to the most demanding passages of play in competitive games.	- Players should be exposed to varied stimulus throughout the training week. - Match HSR and sprinting are only replicated in 10vs10+GKs format.

Abbreviations: $\%HR_{max}$, percentage of maximum heart rate; ACC, accelerations; DEC, decelerations; COD, change of direction; MechW, mechanical work (overall measure of velocity changes and is calculated using ACC, DEC and COD events >2 $m \cdot s^{-2}$); PL, Playerload^{TM} (see section 2.4.5 for review); MDP, most demanding passages of play; GKs, goalkeepers; GPS, global positioning systems, yr, years; HSR, high-speed running.

2.3.2.3 Influence of number of players and pitch area

From the previous sections in this review, it is evident that SSGs are an effective strategy of multicomponent training, and often evoke similar or greater physical, physiological, and perceptual responses to interval training and match-play. However, as presented in Figure 4, numerous variables can be manipulated which should be considered when programming SSG training. The structural format of an SSG is an important consideration that can alter the physical and physiological demands, and therefore may influence adaptations (Casamichana & Castellano, 2010). Previous work has focused on altering variables such as the number of players, the pitch size, the presence of GKs, the training prescription (i.e., work and rest durations), as well as various other factors (Bangsbo, 1994b; Hill-Haas et al., 2011; Casamichana & Castellano, 2010). The influence of these factors and the current trends within the literature will be discussed in the following section of this review.

Investigating the effects of the player number on exercise intensity is one of the most prevalent topics in SSG research (Sarmento et al., 2018). In both research and practice, the number of players and the pitch size is often adjusted concomitantly, which may explain some discrepancies within the literature (Hill-Haas et al., 2011). However, one aspect that seems clear is that when changing only the number of players whilst keeping other factors similar (e.g., relative area per player, conditions, rules of the game), the formats with fewer players elicit greater exercise intensities (Hill-Haas et al., 2011; Aguiar et al., 2013; Sarmento et al., 2018; Bujalance-Moreno, Latorre-Román, & Garcia-Pinillos, 2019). Typical responses seen in games with low player numbers (i.e., 1 vs 1 – 5 vs 5) are $\%HR_{max}$ values of ~85 – 90% (Impellizzeri et al., 2006; Little & Williams, 2007; Rampinini et al., 2007c; Katis & Kellis, 2009; Owen et al., 2011; Dellal et al., 2012a; Köklü, 2012), BLa concentrations of ~4 – 8 $mmol \cdot L^{-1}$ (Aroso, Rebelo, & Gomes-Pereira, 2004; Dellal et al., 2011a; Hill-Haas et al., 2009b; Rampinini et al., 2007c) and RPE (Borg CR-10 scale) values of ~7.6 – 8.5 AU (Rampinini et al., 2007c). Based on these findings, it is suggested that when the aim is to target training at or above the anaerobic threshold (~BLa >4 $mmol \cdot L^{-1}$), then these formats of SSG can be a useful tool (Clemente et al., 2014a). A factor that is likely to be contributing to these responses is a higher number of player interactions and frequency of ball contacts when fewer players are involved (Jones & Drust, 2007; Katis & Kellis, 2009; Owen et al., 2011). However, it should be noted that whilst the frequency of technical actions is increased with fewer players, the tactical component of the SSG may be limited, as players are less restricted to specific positional tasks (Turner & Stewart, 2014).

Another key variable that is often manipulated during SSGs is the pitch area size, both in absolute terms and relative to player number (Owen et al., 2004; Tessitore et al., 2006; Rampinini et al., 2007c; Kelly & Drust, 2009; Casamichana & Castellano, 2010; Hill-Haas et al., 2011; Hodgson et al., 2014; Castellano et al., 2015). The rationale for this is clear, as the playing dimensions have been shown to manipulate the physical and technical demands placed on players (Casamichana & Castellano, 2010). Studies are not always in agreement on the influence of pitch size on the physiological response of the players. Whilst the consensus in the literature is that greater area sizes per player result in higher metabolic and perceptual responses (Aroso et al., 2004; Casamichana & Castellano, 2010; Rampinini et al., 2007c; Owen, Twist, & Ford, 2004; Köklü et al., 2013), some have found the opposite (Tessitore et al., 2006) or reported no differences (Kelly & Drust, 2009). Nevertheless, a likely factor explaining why most studies report an increase in intensity in a larger area size per player is due to the increased space each player must cover, and therefore a decreased opportunity for recovery (Clemente et al., 2014b). However, inconsistency in the number of players per team, or the presence of GKs, could explain the minor inconsistencies in the literature (Rampinini et al., 2007c; Castellano et al., 2013).

With regards to the external demands, there is a general agreement across the literature that SSGs played with lower player numbers (e.g., 1 vs 1 – 5 vs 5) result in more changes in velocity (Hodgson et al., 2014; Lacome et al., 2018) and less HSR (Casamichana & Castellano, 2010; Castellano et al., 2015; Lacome et al, 2018) than larger formats (e.g., 6 vs 6 – 10 vs 10). Although this relationship is likely to be very dependent on the pitch area size per player. Previous work in soccer has associated both changes in velocity (Nedelec et al., 2014) and HSR (Thorpe & Sunderland, 2012; Hader et al, 2019) with fatigue in the hours and days that follow 11 vs 11 matches. Therefore, given the popularity of SSGs in soccer training, it seems prudent that the responses to SSGs are also investigated, considering the impact this may have on the ability to train other important components throughout the training week. A summary of the key studies that have investigated the influence of changing the number of players and/ or the pitch area is presented in Table 4.

Table 4. Summary of key studies that have investigated the influence of changing the number of players and/ or the pitch size during SSGs.

Study	Sample	Player number	Pitch dimensions	Area per player	Training regimen (work/rest)	Key results	Findings
Little & Williams (2007)	28 elite players	- 2vs2+GKs - 3vs3+GKs - 4vs4+GKs - 5vs5+GKs - 6vs6+GKs - 8vs8+GKs	- 30x20 yd - 43vs25 yd - 40x30 yd - 45x30 yd - 50x30 yd - 70x45 yd	- 150 yd^2 - 175 yd^2 - 150 yd^2 - 135 yd^2 - 125 yd^2 - 197 yd^2	- 4x2-min/1-min - 4x3:30-min/1.30-min - 4x4-min/2-min - 4x6-min/1.30-min - 3x8-min/1.30-min - 4x8-min/1.30-min	Mean $\%HR_{max}$; RPE (AU, Borg 20-point scale) reported: ~ 88.5%; 16 AU ~ 91%; 15.5 AU ~ 90%; 15.5 AU ~ 89%; 14.5 AU ~ 87.5%; 13.5 AU ~ 88%; 14 AU	- All formats assessed appear appropriate for development of aerobic properties - Non-significant correlation (r = 0.60) between HR and RPE, likely due to different training regimen. - Smaller formats (2vs2-4vs4) may be more suited to anaerobic development.
Rampinini et al. (2007c)	20 amateur players	- 3vs3 - 4vs4 - 5vs5 - 6vs6	- 12x20, 15x25, 18x30 m - 16x24, 20x30, 24x36 m - 20x28, 25x35, 30x42 m - 24x32, 30x40, 36x48 m	- 40, 63, 90 m^2 - 48, 75, 108 m^2 - 56, 88, 126 m^2 - 64, 100, 144 m^2	- 3x4-min/3-min - 3x4-min/3-min - 3x4-min/3-min - 3x4-min/3-min	Mean $\%HR_{max}$; RPE (AU, Borg CR-10 scale); BLa ($mmol \cdot L^{-1}$) reported: - 89.4 $\%HR_{max}$; 5.5 AU; 7.6 $mmol \cdot L^{-1}$ average of all sizes. - 88 $\%HR_{max}$; 5.0 AU; 7.2 $mmol \cdot L^{-1}$ average of all sizes. - 87.4 $\%HR_{max}$; 4.8 AU; 6.8 $mmol \cdot L^{-1}$ average of all sizes. - 85.7 $\%HR_{max}$; 4.2 AU; 6.3 $mmol \cdot L^{-1}$ average of all sizes.	- Exercise intensity decreased with higher player numbers. - Exercise intensity increased with larger pitch area with the same player number. - Coach encouragement significantly increased the exercise intensity for all SSGs assessed.
Kelly & Drust (2008)	8 u-19 players.	- 4vs4+GKs	- 30x20 m - 40x30m - 50x40 m	- 75 m^2 - 150 m^2 - 250 m^2	- 4x4-min/ 2-min - 4x4-min/ 2-min - 4x4-min/ 2-min	Mean $\%HR_{max}$; number of technical actions reported: - 91 $\%HR_{max}$; more tackles & shots than other conditions. - 90 $\%HR_{max}$ - 99 $\%HR_{max}$	- Changes in pitch size do not alter the HR or the majority of technical requirements during SSGs.
Katis & Kellis (2009)	34 u-15 players.	- 3vs3+GKs - 6vs6+GKs	- 15x25 m - 30x40 m	- 62.5 m^2 - 100 m^2	- 10x4-min/3-min - 10x4-min/3-min	Mean $\%HR_{max}$; number of technical actions reported: - 87.6 $\%HR_{max}$ - 82.8 $\%HR_{max}$; less technical actions with the exception of long passes and headers.	- 3vs3 induced higher HR response - More short passes, kicks, dribbles, tackles and goals in 3vs3 compared to 6vs6. - More long passes and headers in 6vs6.
Casamichana & Castellano (2010)	10 u-17 players.	- 5vs5+GKs	- 32x23 m - 50x35m - 62x44 m	- 73.6 m^2 - 175 m^2 - 272.8 m^2	- 1x8-min - 1x8-min - 1x8-min	Mean $\%HR_{max}$; total distance; HSR (m, >18 $km \cdot h^{-1}$); RPE (AU, Borg CR-10); technical actions reported: - 86.0 $\%HR_{max}$; 696m; 4.9m; 5.7 AU - 88.5 $\%HR_{max}$; 909m; 28.5; 6.7 AU - 88.9 $\%HR_{max}$; 1000m; 74.2m; 6.7 AU	- As the pitch area size increases total and HSR distance, along with the physiological load. - Smaller pitch results in more technical actions (interceptions, control, dribble, shoot, clearance).

Dellal et al. (2011)	27 elite u-17 players.	- 2vs2 - 3vs3 - 4vs4	- 20x25 m - 25x30 m - 28x35 m	- 125 m^2 - 125 m^2 - 122.5 m^2	- 8x2-min/ 1-min - 6x3-min/ 1.30-min - 4x4-min/ 2-min	Mean %HRR & BLa ($mmol \cdot L^{-1}$) reported: - 80.1 %HRR, 6.32 $mmol \cdot L^{-1}$ - 80.5 %HRR, 7.48 $mmol \cdot L^{-1}$ - 70.6 %HRR, 7.07 $mmol \cdot L^{-1}$	- Physiological demands are higher during 2vs2 and 3vs3 compared to 4vs4. - Homogeneity lower (<CVs) in 4vs4 compared to other games.
Owen et al., (2011)	15 elite players.	- 3vs3+GKs - 9vs9+GKs	- 30x25 m - 60x50 m	- 125 m^2 - 167 m^2	- 3x5-min/ 4-min - 3x5-min/ 4-min	Mean $\%HR_{max}$; number of technical actions reported: - 90±2.4 $\%HR_{max}$; more dribbles, shots, tackles & touches. - 81±5.5 $\%HR_{max}$; more blocks, headers, passes, receives & interceptions.	- 3vs3 induced significantly higher exercise intensity than 9vs9. - Technical actions during 3vs3 more suitable for midfielders and attackers, whereas during 9vs9 more suitable for defenders.
Köklü (2012)	20 u-17 players	- 2vs2 - 3vs3 - 4vs4	- 15x20 m - 18x24 m - 24x36 m	- 75 m^2 - 72 m^2 - 108 m^2	- 3x2-min/ NR - 3x3-min/ NR - 4x3-min/ NR	Mean $\%HR_{max}$; BLa ($mmol \cdot L^{-1}$) reported: - 88.6 $\%HR_{max}$; 7.8 $mmol \cdot L^{-1}$ - 92.0 $\%HR_{max}$; 6.8 $mmol \cdot L^{-1}$ - 90.1 $\%HR_{max}$; 6.7 $mmol \cdot L^{-1}$	- $\%HR_{max}$ significantly higher for 3vs3 than 2vs2 and 4vs4. - BLa significantly higher for 2vs2 compared to 3vs3 and 4vs4.
Köklü et al. (2013)	16 u-15 players	- 3vs3 - 4vs4	- 20x15 m - 25x18m - 30x20m - 20x20 m - 30x20m - 32x25m	- 50 m^2 - 75 m^2 - 100 m^2 - 50 m^2 - 75 m^2 - 100 m^2	- 4x3-min/2-min - 4x3-min/2-min - 4x3-min/2-min - 4x4-min/2-min - 4x4-min/2-min - 4x4-min/2-min	Mean $\%HR_{max}$; RPE (AU, Borg CR-10 scale) reported: - 87.1 $\%HR_{max}$; 5.2 AU - 89.0 $\%HR_{max}$; 5.6 AU - 91.9 $\%HR_{max}$; 6.1 AU - 86.5 $\%HR_{max}$; 4.4 AU - 88.9 $\%HR_{max}$; 5.0 AU - 90.7 $\%HR_{max}$; 5.3 AU	- Increased pitch size per player results in higher exercise intensity.
Castellano et al. (2015)	24 elite youth players	- 7vs7+GKs - 9vs9+GKs -10vs10+GKs	- 45x27, 63x38, 78x46 m - 52x31, 73x44, 90x54 m - 58x35, 82x49, 100x60 m	- 100, 200, 300 m^2 - 100, 200, 300 m^2 - 100, 200, 300 m^2	- 2x12-min/5-min - 2x12-min/5-min - 2x12-min/5-min	Mean $\%HR_{max}$; total distance (m), PL (AU), HSR (m, >16 $km \cdot h^{-1}$) reported for each condition: - 82, 87, 88 $\%HR_{max}$; 1816, 2085, 2307 m; 267, 285, 300 AU; 48, 115, 202 m - 83, 85, 85 $\%HR_{max}$;1845, 2003, 2250 m; 233, 246, 271 AU; 70, 107, 164 m - 81, 89, 88 $\%HR_{max}$;1766, 2148, 2314 m; 229, 274, 306 AU; 62, 179, 200 m	- Increased pitch size per player increases total and HSR distance. - The relative area per player has a higher influence on the physical demands than the number of players.
Hulka, Weisser, & Belka (2016)	29 u-19 players.	- 5vs5 - 5vs5+GKs	- 28x20 m - 25x35m - 42x30 m - 28x20 m - 25x35m - 42x30 m	- 56 m^2 - 87.5 m^2 - 126 m^2 - 56m^2 - 87.5 m^2 - 126 m^2	- 3x4-min/3-min - 3x4-min/3-min - 3x4-min/3-min - 3x4-min/3-min - 3x4-min/3-min - 3x4-min/3-min	Mean $\%HR_{max}$; RPE (AU, Borg CR-10); total distance (m) reported: - 87.4 $\%HR_{max}$; 4.7 AU; 356 m - 91.7 $\%HR_{max}$; 5.7 AU; 367 m - 89.5 $\%HR_{max}$; 7.1 AU; 489 m - 84.8 $\%HR_{max}$; 4.9 AU; 372 m - 87.2 $\%HR_{max}$; 5.1 AU; 373 m - 88.6 $\%HR_{max}$; 7.5 AU; 497 m	- Larger pitch increased HR and RPE. - Inclusion of GKs decreased workload of players on the small pitch, but not medium and large pitches.

Abbreviations: $\%HR_{max}$, percentage of maximum heart rate; %HRR, percentage of heart rate reserve; GKs, goalkeepers; BLa, blood lactate; RPE, rating of perceived exertion; NR, not reported; PL, Playerload™ (see section 2.4.5 for review); HSR, high-speed running; AU, arbitrary units.

2.3.2.4 Use of goals and goalkeepers

Another common format modification is whether GKs with goals are included or removed, and SSGs played with their removal is typically defined as 'possession play'. Several studies have investigated the influence of these factors and the findings are conflicting (Mallo & Navvaro, 2008; Castellano et al., 2013; Gaudino et al, 2014; Köklü et al, 2015; Hulka, Weisser, & Belka, 2016). Some studies have reported that the addition of goals and GKs reduces the intensity in comparison to possession play (Dellal et al., 2008; Mallo & Navvaro, 2008; Castellano et al., 2013; Köklü et al., 2015). For example, Mallo and Navarro (2008) reported a decrease in %HRmax, total and HSR distance in 3 vs 3 SSGs with goals and GKs in comparison to possession play. This is supported by Castellano et al. (2013b), who reported that indicators of both internal and external load decrease when SSGs are played with goals and GKs. The authors suggested that the reduced physiological responses and movement demands were associated with an increased defensive organization and a higher likelihood for players to maintain positioning, thus decreasing the tempo of play (Castellano et al., 2013). In contrast, Gaudino et al. (2014) reported that the total distance, HSR (19.8–25.2 km.h-1) and sprinting (>25.2 km.h-1) distances, as well as acceleration and deceleration variables, were higher in SSGs played with regular goals and GKs than without. Similarly, Dellal et al. (2008) reported an 11% increase in HR responses when goals and GKs were included during 8 vs 8 SSGs. Here, the authors concluded that the presence of GKs may have increased motivation to attack and defend, therefore increasing the physiological load. Interestingly, Hulka, Weisser, and Belka (2016) found that during 5 vs 5 SSGs, the inclusion of goals and GKs decreased the workload of the player on a small pitch (28 × 20 m), but not on a medium (25 x 35 m) or large (42 x 30 m) pitch. Therefore, pitch size may be an important factor in whether the inclusion of GKs affects the intensity of play. To date, the influence of goals and GKs on exercise intensity during SSGs is unclear, and it is possibly dependent on the number of players or the pitch size. However, their inclusion likely plays an important role in keeping team structures and formations intact, as well as increasing motivation and communication between players. Furthermore, it could be argued that their inclusion is more representative of competitive 11 vs 11 matches.

2.3.2.5 Coach encouragement

Direct supervision and coaching during training has been shown to increase exercise intensity in a variety of settings (Halouani et al., 2014). Indeed, this relationship has also been demonstrated in soccer, and active and consistent coach encouragement has a positive influence on training intensity. A comprehensive study by Rampinini et al. (2007c) investigated the effect of coach encouragement in 20 amateur players on HR, BLa, and RPE responses during various SSG formats (i.e., 3 vs 3 – 6 vs 6) played on small, medium, and large pitches (Table 4). The authors observed that during all SSG formats, all markers of training intensity (i.e., HR, BLa and RPE) were significantly higher during situations when the coach was actively providing encouragement. Similarly, Sampaio et al. (2007) reported a significant increase in RPE for 2 vs 2 and 3 vs 3 SSGs with verbal encouragement, but no significant change in the $\%HR_{max}$. Together, these studies provide evidence that direct coach encouragement is important when the aim is to achieve high exercise intensity during SSGs.

2.3.2.6 Training prescription

Typically, SSGs in the context of soccer training are programmed in the form of intervals (e.g., a set number of repetitions of ~2 – 10-min) as opposed to continuous durations (e.g., >20-min), despite competitive 11 vs 11 matches being split into two 45-min halves (Aguiar et al., 2013). Several studies have investigated the influence of interval vs continuous SSG training. Hill-Haas et al. (2009c) compared continuous (24-min) vs interval (4 x 6-min with 90 s rest) training prescriptions across three different SSG formats (2 vs 2, 4 vs 4, 6 vs 6). Whilst RPE and $\%HR_{max}$ were significantly higher in continuous compared with interval play, the distances covered at higher speed (13 – 18 $km{\cdot}h^{-1}$) and the number of sprints (>18 $km{\cdot}h^{-1}$) were higher during the interval format, despite the total distance being similar between formats. The differences in both the physical and physiological demands are likely explained by the recovery period in the interval format enabling the players to start subsequent bouts with a lower $\%HR_{max}$, and therefore produce a higher intensity of play. In contrast, Köklü (2012) compared training prescription during various SSGs (2 vs 2, 3 vs 3, 4 vs 4) and observed that interval and continuous formats produced similar physiological responses ($\%HR_{max}$ & BLa), concluding that both methods could be used for the targeted physiological adaptations. However, it should be noted that the duration of play in this study was shorter (interval, 3 x 2 – 4-min; continuous, 1 x 6 – 12-min) than those of the previously mentioned study by Hill-Haas et al (2009c). This may go some way in explaining the differences between studies. Taken together, whilst there may be differences in the physical demands and physiological responses between continuous and interval SSG training, it appears neither method has one major advantage over the other, supporting the efficacy of both for training (Hill-Haas et al., 2009c; Köklü, 2012). It could be suggested that increased high-intensity movement demands during interval prescriptions may elicit more anaerobic metabolism, however, continuous SSG play is likely to result in greater and prolonged HR responses which is arguably more characteristic of competitive matches.

2.3.2.7 Small-sided games summary

From reviewing the SSG literature, it is clear that they can be an effective training method that provides similar physiological responses to various modes of running-based interval training, whilst replicating some of the movement and technical demands of competitive games. The format of an SSG is an important factor, and a multitude of variables can be manipulated to alter the demands. However, to the author's best knowledge, there is no research on the fatigue responses to SSGs in the hours and days that follow their performance. This may influence their scheduling within a training program, and a better understanding of how they may interact with other activities a coach wishes their athletes to perform may be beneficial. To gain a better understanding of the responses to an activity, it is firstly important to quantify the demands of that activity. To do this precisely, the methodology should be reliable and valid, and possible limitations should be acknowledged. Therefore, section 2.4 will summarise the literature regarding time-motion analyses in team sport, with a primary focus on GPS devices and their use in soccer.

2.3.3 Strength and power

Training with the intentions of developing strength and power is an integral component of physical preparation programs for many athletes (Young, 2006). Whilst maximal strength refers to the maximum force that can be performed by the neuromuscular system during a maximum voluntary contraction (i.e., one repetition maximum [1RM]), power is the product of force and velocity and refers to the ability of the neuromuscular system to produce a high level of force in a short timeframe (Stølen et al., 2005). A fundamental relationship exists between strength and power, which dictates that an athlete cannot express a high level of power without first being relatively strong (Cormie, McGuigan, & Newton, 2011b). This is supported by the numerous studies revealing that individuals with greater strength have markedly superior power production capabilities than those with a lower level of strength (Moss et al., 1997; Blackburn & Morrissey, 1998; Stone et al., 2003; Carlock et al., 2004; Miyaguchi & Demura, 2008; Nuzzo et al., 2008; Baker, & Newton, 2008; Cormie, McBride, & McCaulley, 2009; Cormie, McGuigan, & Newton, 2010b). Furthermore, an increase in maximal strength is usually associated with an improvement in relative strength to bodyweight ratio, and therefore, an enhanced ability to express power (Baker & Nance, 1999). Indeed, strong, and positive relationships (r = 0.77 – 0.94) between 1RM and maximum power have been reported in a range of populations (Moss et al., 1997; Baker, 2001; Baker, 2002; Stone et al., 2003).

With regards to soccer, many key game demands (e.g., kicking, sprinting, changing direction, jumping, tackling) involve repeated powerful movements, and indeed, the ability to exert a large amount of force in a short timeframe underpins the performance of these tasks. The relationship between strength and power characteristics of the lower body and the ability to perform the above mentioned key game demands is well established in previous literature (Wisloff, Helgerud, & Hoff, 1998; Wisloff et al., 2004; Cronin & Hansen, 2005; Kotzamanidis et al., 2005; Ronnestad et al., 2008; West et al., 2011; Ferrete et al., 2014; Silva, Nassis, & Rebelo, 2015; Thomas et al., 2015; Wing, Turner, & Bishop, 2018; Northeast et al., 2019; Boraczyński et al., 2020; Möck et al., 2021). For example, Wisloff et al. (2004) reported significant correlations between lower body strength and 10 m sprint times (r = 0.94, $p < 0.001$), 30 m sprint times (r = 0.71, $p < 0.01$), COD ability (r = 0.68, $p < 0.02$), and JH (r = 0.78, $p < 0.02$) in 17 elite male soccer players (Figure 5). Another example of the benefits achieved by strength training can be seen in a study conducted in a Champions League team during an 8-week pre-season (Helgerud et al., 2011). Players were unfamiliar with strength training as part of their training, and an intervention was introduced with the aim of increasing neural adaptation (i.e., 4 sets of 4 repetitions at 90% 1RM in the half squat). Strength training sessions were completed twice per week and only took ~15-min to complete. Players improved their half-squat 1RM from 116 to 176kg and vertical JH increased from 57.2 to 60.2 cm. 10 m sprint time result was reduced from 1.87 to 1.81 s, and 20 m sprint time improved from 3.13 to 3.08 s. In another study, Arnason et al. (2003) found that final league standing was significantly related to team average CMJ height and leg extension power in 15 professional teams in the top Icelandic league. With regards to technical actions, Wing, Turner and Bishop (2018) observed a significant relationship between CMJ height and heading success (r = 0.80), as well as 1RM squat strength and tackle success (r = 0.61), in 15 young soccer players analysed over

16 competitive matches. Whilst maximal strength training is known to improve running economy (RE) in distance runners (Denadai et al., 2017), Hoff and Helgerud (2003) reported significant improvements in RE (+ 4.7%) in soccer players after a maximal strength training intervention that improved their half-squat 1RM by 33%, despite no changes in body weight or VO_{2max}.

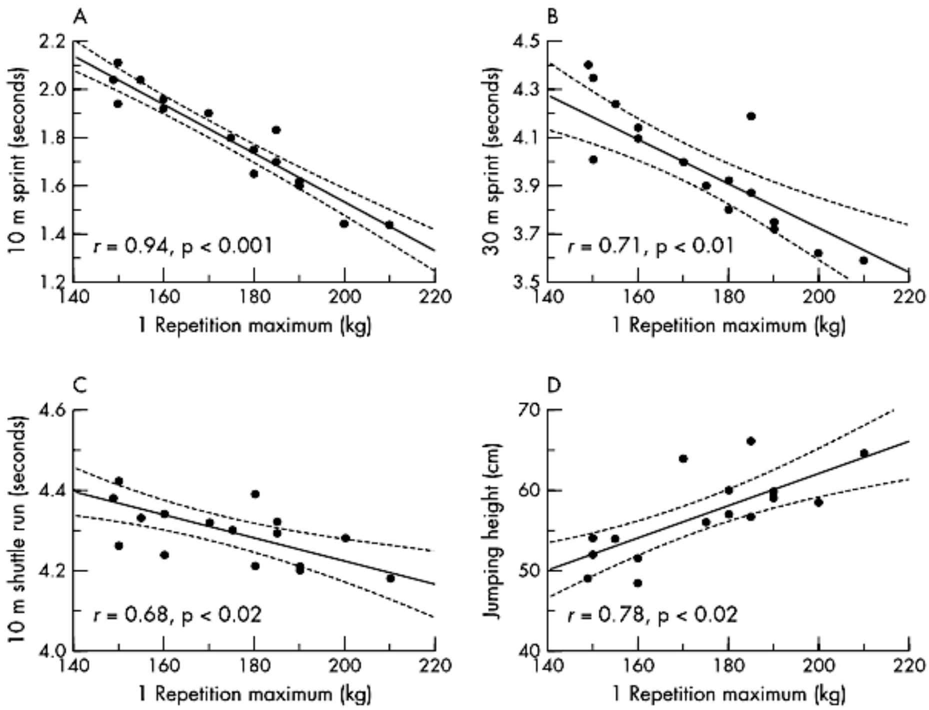

Figure 5 (A – D). Relationship between half squat 1RM and 10 m sprint (**A**), 30 m sprint (**B**), 10 m shuttle (**C**), and vertical jump height (**D**) in elite soccer players. Reproduced from Wisloff et al. (2004).

Aside from the above-mentioned performance benefits of enhanced strength and power, there is convincing evidence that these physical qualities influence other key mechanisms related to soccer performance. Owen et al. (2015) reported a significant correlation (*moderate – very large*) between lower body force production and indices of muscle damage (i.e., creatine kinase [CK] concentration) at 48 hours after matches in elite soccer players. This data is reinforced by those of Johnston et al. (2015b), who reported that the post-match fatigue response is lower in rugby players with better developed lower body strength and HSR ability, despite these players having greater internal and external match loads. Furthermore, there is an abundance of evidence that greater strength is related to decreased injury risk (Lehnhart et al., 1996; Fleck & Falkel, 2007; Folland & Williams, 2007; Croiser et al., 2008; Opar et al., 2015). For example, Lehnhart and colleagues (1996) demonstrated that the introduction a strength training regimen to a soccer team reduced the number of injuries by ~50%. Reduced injury rates and severity are known to have a significant impact on team performance, as research indicates that a higher squad availability coincides with a higher league placing over a season (Hagglund et al., 2013; Carling et al., 2015).

2.3.3.1 Resistance training type

Various exercise modalities have been used in an attempt to develop strength and power. These include compound resistance exercises, ballistic exercises, weightlifting derivatives (i.e., clean, jerk, snatch), plyometrics, velocity-based training, isometric training, isolation exercises, and sport-specific strength-based actions (Turner & Stewart, 2014; Silva, Nassis, & Rebelo, 2015). The specific exercises, sets, repetitions, volume, and intensity vary greatly across studies, and the content of resistance training programs are likely to differ between teams and are dependent on the philosophy of the club staff and the individual needs of the players. However, Silva and colleagues (2015) conducted a review of 24 manuscripts including a total of 523 soccer players and concluded that high-intensity resistance training (e.g., strength training; ≤6 repetitions; ≥80% 1RM; ≥3-min recovery) is more efficient than moderate-intensity resistance training (e.g., hypertrophy training; ≥8 repetitions; 70 – 75% 1RM; ≤2-min recovery) in improving jumping ability, 10 m acceleration time and maximal speed. Furthermore, Cormie, McGuigan, and Newton, (2011b) conducted a non-soccer specific review and highlighted the abundance of training studies revealing that heavy strength training results in not only enhanced maximal strength but also enhanced power. Therefore, it is well established that enhancing and maintaining maximal strength is essential when considering the long-term development of power (Cormie, McGuigan, & Newton, 2011b). Whilst the mechanisms underpinning strength adaptations are often thought to be primarily associated with increases in the cross-sectional area of the muscle, improvements in strength are often observed without noticeable hypertrophy which indicates that neural adaptations are a very important factor (Gabriel, Kamen, & Frost, 2006). This suggests that more strength does not necessarily equate to an increase in muscle mass and several distinct adaptations can lead to similar effects (Toigo & Boutellier, 2006). In this regard, many of the adaptations to heavy resistance training (≥80% 1RM), power and ballistic training are primarily attributed to neural adaptations, such as enhanced motor unit recruitment and synchronisation, rate coding (frequency or rate of action potentials), and intra-muscular coordination (Aagaard et al., 2002; Cormie, McGuigan, & Newton, 2011b). With regards to athletes such as soccer players, where the demands are primarily non-contact compared to rugby or NFL players, this is an important consideration. Although somewhat position-dependent, ideally soccer players would increase their relative strength to bodyweight ratio so that their ability to run, sprint and change direction is not compromised. Therefore, heavy resistance exercise and/ or explosive and ballistic exercises are generally recommended in soccer players to increase neuromuscular performance without a concomitant increase in body mass (Silva et al., 2015).

2.3.3.2 Resistance training frequency

As mentioned in the previous sections of this review, the high fixture demand in soccer limits the availability of time to train physical qualities (Morgans et al., 2014). From a training frequency perspective, Ronnestad and colleagues (2011) observed that one strength training session per week during the first 12 weeks of the in-season period resulted in a sufficient training stimulus for maintaining the pre-season (two sessions per week for 10 weeks) gains in strength, jump, and sprint performance of professional players. However, a lower weekly in-season volume (one session every two weeks) resulted in detraining of all variables apart from jump performance (Ronnestad, Nymark, & Raastad, 2011). Koundourakis et al. (2014) investigated the resistance training frequency of three professional teams. Team (a) performed two sessions per week, whereas team (b) and (c) performed only one resistance training session per week. All teams exhibited greater neuromuscular performance in the middle of the season in comparison to the start of the season. Yet only team (a) that performed a higher number of resistance training sessions displayed improved neuromuscular performance during the end phase of the season. Furthermore, team (a) showed higher total testosterone concentrations throughout the season compared to teams (b) and (c). The authors concluded that the elevation of endogenous androgens as a result of a higher volume of strength training indicated that the best method to improve athletic performance is consistent intense training. In summary, it has been shown that two weekly sessions of strength training are sufficient to increase strength and power, with one weekly session being adequate to avoid in-season detraining

2.3.3.3 Summary of strength and power training in soccer

Strength and power are fundamental physical qualities that underpin performance in soccer. Furthermore, enhancing and maintaining strength is essential in underpinning the long-term development of power (Cormie, McGuigan, & Newton, 2011b). Given this, soccer players should aim to concurrently develop and maintain aerobic capacity along with strength and power. However, there is evidence that the simultaneous integration of resistance and endurance exercise into a training program (i.e., concurrent training) compromises the development of strength and power in comparison to undertaking resistance training alone (Hickson, 1980; Leveritt et al., 1999; Wilson et al., 2012; Fyfe, Bishop, & Stepto, 2014). Whilst the mechanisms for this 'interference effect' are likely multifactorial, possible reasons are that the endurance exercise interferes with the ability to perform the resistance training sessions (via residual fatigue and/ or substrate depletion; Leveritt et al., 1999), as well as moderations in the acute molecular responses that mediate strength and power adaptation (Baar, 2006; Hawley, 2009). This is a key programming consideration and practitioners should have an understanding of the factors that may influence this interference effect. More detail on concurrent training is provided in section 2.8.3 of this review.

2.4 GLOBAL POSITIONING SYSTEMS

GPS refers to satellite-based navigation originally developed by the US military in the early 1970s. By the 1980s it was made available for civilian use and has been applied to a variety of settings since, including sports (Aughey, 2011; Cummins et al., 2013). Fundamentally, orbiting satellites transmit radio signals that allow for the calculation of the time it takes for a signal to travel from the satellite to a GPS receiver on earth (Cummins et al., 2013). If at least four satellites are synchronised with a GPS receiver, the distances between satellites and a GPS device can be calculated, and through a series of trigonometric calculations, the specific location of the receiver can be determined (Larsson, 2003; Witte & Wilson, 2004). Once the location of the GPS receiver is known, its displacement over a given time can be used to calculate the velocity of movement. This is of interest to coaches, athletes, scientists, and others associated with sports performance (Aughey, 2011; Cummins et al., 2013).

The first research paper attempting to validate the use of GPS in quantifying human locomotion was published by Schutz and Chambaz (1997). A single participant undertook 76 different trials (i.e., 19 walking, 22 running, and 35 cycling) at constant velocities whilst equipped with an early commercially available device (GPS 45, Garmin) and was compared against a Swiss certified chronometer. A near-perfect correlation (r = 0.99) was observed between the displacement measured by the GPS device and the chronometer. Despite this promising early research, it was clearly limited in its application to team sport as the path taken by an athlete involves regular changes in direction and velocity (Aughey, 2011). In addition, for use in sport a GPS device had to be light (early devices weighted up to ~4 kg) and able to withstand heat, moisture, and impacts (Aughey, 2011). Modern devices are now small and robust enough to be harnessed between an athlete’s scapulae during training and matches (Figure 6). After the pioneering research by Schutz and Chambaz (1997), it would still be more than a decade before research quantifying the reliability and validity of GPS in tracking team sport movement was published. As the technology increased in sampling frequency (range, 1 – 20 Hz), the early literature on GPS moved on from validating steady-state displacement at a set velocity to quantification of sport-specific movements on the field (Aughey, 2011). The use of GPS is now commonplace in monitoring the movement demands in sport, and the following sections will discuss its application, reliability, and validity in tracking sporting movements in general, with a specific focus on soccer.

Figure 6. Vest garment designed to harness a GPS unit (Catapult, Australia).

2.4.1 The use of global positioning systems in team sport

The current literature provides an array of information on the GPS measured training and match activity profiles of athletes across numerous team sports (e.g., AFL, rugby codes, cricket, Gaelic football, hockey, tennis, and soccer). Furthermore, there is an abundance of literature investigating the reliability and validity of GPS devices for the measurement of team sport activity, which will be discussed in sections 2.4.3 and 2.4.4. External load (i.e., GPS data) is often used in conjunction with internal load (i.e., HR) and perceptual responses (i.e., RPE) to provide a holistic assessment of physical exertion. Generic uses of GPS in sport include profiling the match demands, assessment of competition performances and establishing training loads (Cummins et al., 2013).

Traditionally, GPS was used to measure basic components of player movement, with the most prominently reported metrics being total distance, distance covered at various speed thresholds, and the number of acceleration and deceleration efforts (Cummins et al., 2013). More recently, the integration of a tri-axial accelerometer sampling at 100 Hz within the GPS unit enables the measurement of a composite vector magnitude (expressed as G-force) by recording the sum of accelerations measured in three planes of movement (X, Y, and Z axes). In addition, gyroscopes and magnetometers are embedded within the GPS unit to measure rotational forces and the orientation of an athlete's body (Figure 7). Through this integration of technology, accelerometers can quantify the summation of all forces acting on an athlete's body, including impacts with other athletes, objects, and surfaces (Cummins et al., 2013). These metrics are of particular interest in contact sports, and inevitably add to the broader understanding of workload in rugby and contact football codes (McLellan, Lovell, & Gass, 2011; Gabbett, Jenkins, & Abernethy, 2012; Suarez-Arrones et al., 2012; Cunniffe et al., 2009). In addition, accelerometers can work independently from the GPS and are therefore very useful for indoor sports, such as basketball and netball.

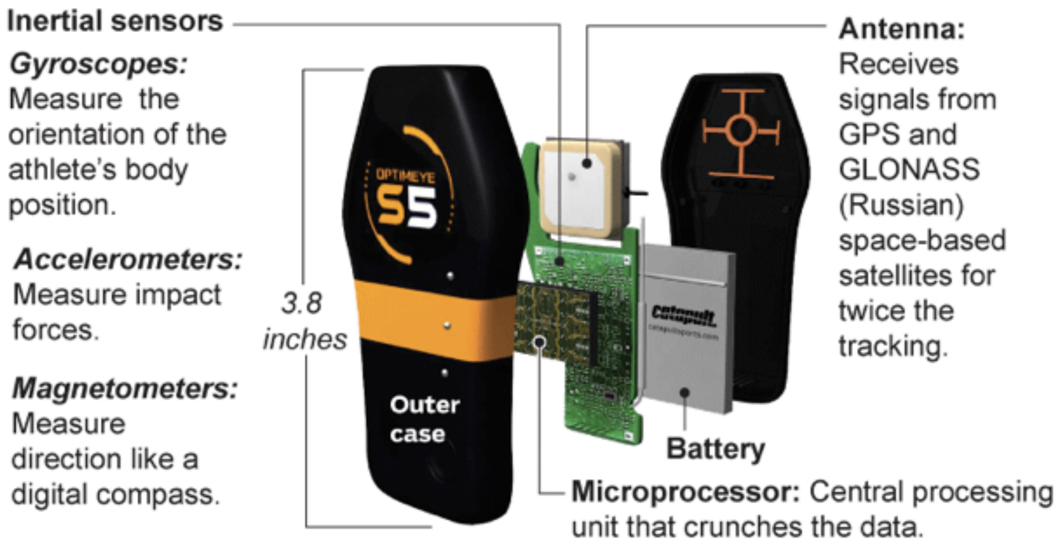

Figure 7. Components of a GPS unit (Catapult S5 Unit, Australia).

2.4.2 Time-motion analysis in soccer and relationships between tracking systems

The methods for assessing time motion analysis in soccer have developed progressively over time. Pioneering studies used a single camera to record and analyse each player individually (Reilly & Thomas, 1976) but were labour intensive, subjective, and susceptible to human error. More contemporary approaches such as multi-camera semi-automated systems (i.e., ProZone, Amisco) can gather a more objective analysis of match-play (Di Salvo et al., 2007). However, it is unlikely that teams will have camera systems installed at their training facilities, making comparisons between training and games challenging (Buchheit et al., 2014b; Linke et al., 2018). More recently, GPS has circumvented the more traditional time-motion analysis methods. This is largely due to the ability of practitioners to use the same tracking system during both training and matches, and the ability of GPS to quantify the acceleration and accelerometry demands that could not previously be obtained by fixed speed thresholds with camera analyses (Harley et al., 2010; McLellan, Lovell, & Gass, 2011; Dwyer & Gabbett, 2012). The governing body of soccer (i.e., FIFA) approved the use of GPS in competitive matches in 2015, however, some teams still refrain from using GPS in competitive matches, relying instead on camera systems for tracking data. This may be due to the reluctance of players in wearing a GPS vest in matches, or the benefit of obtaining opposition data from the cameras for between-team comparisons. However, using different systems interchangeably to measure the same athlete over time is problematic for several reasons (Carling, 2013; Buchheit et al., 2014b). Whilst cameras can capture locomotor activities such as the distances covered and the frequency and distribution of efforts performed at given speeds (Bradley et al., 2009; Mohr, Krustrup, & Bangsbo, 2003), this does not consider that acceleration is often maximal even at low absolute speeds (Akenhead et al., 2013; Varley & Aughey, 2013). Furthermore, numerous studies report significant differences in outputs from GPS and camera systems (Randers et al., 2010; Harley et al., 2011; Cook, 2014; Buchheit et al., 2014b; Linke et al., 2018). Randers et al. (2010) compared four different tracking systems (i.e., 1 Hz GPS; 5 Hz GPS, video analysis, computer-based tracking) during the same soccer match. The authors reported that despite detecting similarities in performance decrements throughout the game, there were large between system differences in determining the total distance (1 Hz GPS, 9.52 ± 0.89 km; 5 Hz GPS, 10.72 ± 0.70 km; video analysis, 9.51 ± 0.74 km; computer-based tracking, 10.83 ± 0.77 km). This is supported by Cook (2014), who found that computer-based tracking and semi-automated video analysis overestimated 5 Hz GPS data by 251 ± 81 m and 191 ± 42 m respectively. With regards to high-speed activity, Randers et al. (2010) reported 5 Hz GPS to underestimate HSR (≥18 km·h^{-1}) by 63 m in comparison to a semi-automated tracking system. Yet these differences in agreement were far less in comparison to video analysis and 1 Hz GPS, which underestimated HSR by 104 m and 99 m respectively. These findings are similar to those of Harley et al. (2011), who reported that semi-automated tracking overestimated sprinting (≥25.2 km·h^{-1}) and HSR (19.2 – 25.2 km·h^{-1}) values by 13.8 m and 51.1 m respectively, in comparison to 5 Hz GPS during a competitive match. In an attempt to counteract these differences, some researchers have developed calibration equations so that the data is more comparable (Buchheit et al., 2014b). However, caution should still be used when using this approach, given the moderate typical error of the estimate (Buchheit et al., 2014b). In summary, whilst there are several tracking systems available and there is no 'gold standard' measure, differences between systems exist which makes it problematic when using different systems interchangeably.

2.4.3 Influence of sampling rate on the reliability and validity of global positioning systems

The reliability and validity of GPS has been studied extensively in the last decade across a range of sampling rates (1 – 20 Hz) and in a wide range of team sports. When attempting to compare differences between individuals, a device must hold acceptable inter-unit reliability (Heale & Twycross, 2015). In addition, when aiming to compare the same player over different activities, the same device should produce the same data consistently (intra-unit reliability). Methods in assessing this typically include running the GPS device through a pre-measured course to assess distance, comparing the GPS to timing gates or radar guns for speed, or attaching the unit to an automatic sled to assess instantaneous velocity (Cummins et al., 2013; Akenhead et al., 2014). The need for GPS to hold acceptable inter and intra-unit reliability, as well as a high level of validity, is imperative for those working in elite sport, as important programming decisions are often informed by the data.

Studies investigating the validity and reliability of early commercially available GPS devices sampling at 1 Hz generally reported that they were acceptable at measuring slow to moderate-speed linear locomotion, but the validity and reliability were reduced at higher speeds and over non-linear paths (MacLeod et al., 2009; Coutts & Duffield, 2010; Jennings et al., 2010; Kelly et al., 2014). As the sampling rate increased to 5 Hz, a strong trend across the literature is that both reliability and validity improved in comparison to 1 Hz devices (Barbero-Alvarez et al., 2010; Jennings et al., 2010; Johnston et al., 2012; Petersen et al., 2009). However, the same limitations were present when the speed increased above 20 $km \cdot h^{-1}$, when assessing sprints over shorter distances (<20 m) or when multi-directional movement was introduced (Petersen et al., 2009; Jennings et al., 2010; Johnston et al., 2012). For example, Jennings et al. (2010) reported that the standard error (SE) in 10 m sprints for 1 and 5 Hz GPS were 32.4% and 30.9% respectively. Furthermore, although the 5 Hz system was twice as reliable in comparison to the 1 Hz system, the CV for higher speed runs over shorter distances (10 – 20 m) was poor (17.5 – 39.5%). These findings were confirmed by further studies comparing 1 and 5 Hz GPS devices (Boyd et al., 2011; Johnston et al., 2012). Whilst these studies showed promising results for the future application of GPS, the errors in assessing short and high-speed sprints were major limitations in their application to a team sport. It is clear that these movements are considered key game characteristics that are important to monitor, both for performance and their relationship with fatigue (Thorpe & Sunderland, 2012; Nedelec et al., 2014; Russell et al., 2016b; Hader et al., 2019).

More recent advancements have seen 10 and 15 Hz GPS now commonplace in elite sport and there is a general agreement across the literature that there is a considerable improvement in measuring constant speed and changes in velocity. An early study by Castellano et al. (2011) investigated the reliability and validity of a 10 Hz system. The researchers assessed 15 and 30 m sprints, which were generally the least valid and reliable measures in previous 1 and 5 Hz literature. They reported that the 10 Hz GPS produced more valid (6.5% bias) and reliable (CV 5.1%) results during longer (30 m) compared to the shorter sprints (15 m) (11.9% bias, CV 10.9%) (Castellano et al., 2011). Despite the lower accuracy at high-speed over short distances, this was a clear improvement to the previously studied lower sampling frequency devices (Petersen et al., 2009, Jennings et al., 2010). In this vein, Varley, Fairweather and Aughey (2012) reported that 10 Hz GPS devices were up to six times more reliable than their 5 Hz counterparts. The authors reported CV values for constant velocity, acceleration, and deceleration as ≤5.3%, ≤4.3% and ≤6% respectively for a 10 Hz sampling rate, in comparison to ≤12.4%, ≤16.2% and ≤31.8% for a 5 Hz device. The same authors also reported that 10 Hz GPS devices were two to three times more accurate than 5 Hz devices in assessing velocity measures (constant, accelerating and decelerating) under various starting speeds (1 – 3, 3 – 5 and 5 – 8 $m \cdot s^{-1}$), with a mean bias of 3.6%. As previously mentioned, Jennings et al., (2010) reported that the SE in a 10m sprint for 1 and 5 Hz GPS, was 32.4 and 30.9% respectively. In contrast, the 10 Hz device demonstrated a 10.9% SE over a 15 m sprint (Jennings et al., 2010). It is generally accepted that GPS units sampling at 10 Hz possess an acceptable level of validity and reliability in measuring total distance, short sprints, and changes in velocity (Table 5). Interestingly, research has shown that there may not be an improvement in reliability or validity when the sampling rate increases to 15 Hz. Johnston et al. (2014) compared 10 and 15 Hz devices during a team sport simulation circuit and found no significant difference between the pre-measured distance and the distance reported from both GPS devices. However, the maximum speed reported from both devices was significantly different to the measured peak speed. Yet, given that the average for both sets of devices was within 0.5 $km \cdot h^{-1}$ of the measured speed, this may be acceptable on a practical level (Johnston et al., 2014). Interestingly, whilst both GPS devices were shown to be valid and reliable, the 15 Hz GPS units exhibited lower validity for total distance and average peak speed than the 10 Hz counterparts (Johnston et al., 2014). A summary of the key studies that have investigated the reliability and validity of 10 and 15 Hz GPS is presented in Table 5.

Table 5. Summary of key studies that have assessed the reliability and validity of 10 and 15 Hz GPS.

Study	Aim	Methods	Results	Conclusions
Castellano et al. (2011)	Reliability and accuracy of 10 Hz GPS in sprints of 15 and 30m.	- 9 trained athletes with 1 GPS performed 6 and 7 maximal sprints of 15 m and 30 m respectively (total n = 117 runs). - Compared to timing gates and camera.	- 10 Hz GPS produced more valid (6.5% bias) and reliable (SEM 5.1%) results on 30 m sprints compared to the 15 m distance (11.9% bias, SEM 10.9%). - CV was 1.3% and 0.7% for 15 m and 30 m sprints respectively.	- 10 Hz GPS shows better intra and inter-device reliability in comparison to previous work with 5 Hz devices.
Varley, Fairweather, & Aughey (2012)	Validity and reliability of 5 and 10 Hz GPS for measuring acceleration, deceleration and constant velocity during straight line running.	- 80 straight line running trials were performed by 3 subjects wearing 5 and 10 Hz GPS. - Participants maintained constant speed before accelerating and then decelerating to a stop. - Compared against criterion laser system.	- 10 Hz devices two to three times more accurate than 5 Hz at range of velocities (CV 3.1 – 11.3%) - 10 Hz six times more reliable at measuring instantaneous velocity (CV 1.9 – 6.0%)	- Newer 10 Hz GPS an acceptable tool for the measurement of constant velocity, acceleration, and deceleration during straight-line running.
Akenhead et al. (2014)	Validity and inter-unit reliability of 10 Hz GPS for measuring instantaneous velocity during maximal accelerations.	- Two 10 Hz GPS devices towed on a sled during max 10 m sprint. - Compared to criterion laser measure, which grouped data into acceleration thresholds.	- Mean bias, standard error of the estimate and TE all increased during accelerations of (≥4 $m{\cdot}s^{-2}$).	- The validity and reliability of 10 Hz GPS for the measurement of instantaneous velocity is inversely related to acceleration. - During accelerations ≥4 $m{\cdot}s^{-2}$ accuracy is compromised.

Johnston et al. (2014)	Validity and inter-unit reliability of 10 Hz and 15 Hz GPS units for assessing team sport athlete movement demands.	- 8 trained male participants completed team sport simulation circuit with both GPS devices. - TD and time spent at various speed thresholds assessed.	- 10 Hz units were a valid ($p > 0.05$) and reliable (%TEM = 1.3%) measure of TD. - 15 Hz units exhibited lower validity for TD and average peak speed. - As the speed of movement increased the level of error for the 10 Hz and 15 Hz GPS units increased (%TEM = 0.8-19.9).	- Comparisons should not be undertaken between 10 Hz and 15 Hz GPS units. - 10 Hz GPS units measured movement demands with greater validity and inter-unit reliability than the 15 Hz units.
Rampinini et al. (2015)	Accuracy of 5 Hz and 10 Hz GPS in determining high speed distance and metabolic power in a combination of running speed and acceleration.	- 8 participants performed 56 bouts of an intermittent shuttle run, wearing both 5 Hz and 10 Hz devices. - Compared with radar gun. - Metrics assessed: TD, HSR (>4.17 $m \cdot s^{-1}$), VHSR >5.56 $m \cdot s^{-1}$), Pmean, HMP (>20 $W \cdot kg^{-1}$) and VHMP (>25 $W \cdot kg^{-1}$).	-5 Hz had low error for TD (2.8%) and Pmean (4.5%), whilst the errors for the other variables ranged from moderate to high (7.5-23.2%) - 10 Hz demonstrated a low error for TD (1.9%), HSR (4.7%), Pmean (2.4%) and HMP (4.5%), whereas the errors for VHSR (10.5%) and VHMP (6.2%) were moderate.	- Accuracy increased with a higher sampling rate but decreased with increased speed of movement. - 10 Hz demonstrated a sufficient level of accuracy for quantifying distance covered at higher speeds or time spent at very high power.
Bataller-Cervero et al. (2019)	10 Hz GPS validity and reliability in measuring accelerations and decelerations in straight line running.	- 8 amateur team sport players wore 2 GPS units and performed 2 sets of 21 x 40 m sprints, - First bout at submaximal incremental speed. - Second bout at submaximal incremental speed followed by subsequent submaximal decreasing speed. - Compared against timing gates (mean speed) and a radar gun (instantaneous speed).	-High agreement between GPS devices and the criterion systems - Instantaneous speed (r = 0.98; SMB = -0.07; STE = 0.22); mean speed (r = 0.99; SMB = 0.38; STE = 0.17). - Inter-unit reliability nearly perfect between devices, a trivial SMB and a small STE (r = 0.97; SMB = 0.04; STE = 0.23).	-10 Hz GPS devices are an adequate solution to monitor straight-line running speed in acceleration and deceleration conditions

Abbreviations: GPS, global positioning system; STE, standard typical error; SEM, standard error of the mean; SMB, standardized mean bias; TEM, typical error of the mean; TD, total distance; HSR, high-speed running; VHSR, very high-speed running; Pmean, mean metabolic power; HMP, high metabolic power; VHMP, very high metabolic power; Hz, hertz; CV, coefficient of variation.

2.4.4 Reliability and validity of global positioning systems in assessing acceleration and deceleration

Many key movements in soccer require athletes to accelerate, decelerate and change direction rapidly (Delaney et al., 2018b). These movements are critical in activities such as being first to the ball, moving into space before an opponent, and creating and stopping goal-scoring opportunities (Varley, Fairweather, & Aughey, 2012). In addition, the energy cost of these actions is higher than motion at a constant velocity (Osgnach et al., 2010) and they have the potential to cause significant mechanical and metabolic fatigue (Thorpe & Sunderland, 2012; Russell et al., 2016b; Hader et al., 2019). As such, these variables are very commonly reported, as demonstrated in a survey from 41 elite soccer teams revealing that acceleration variables were perceived as the most important metric when monitoring training (Akenhead & Nassis, 2016). However, whilst studies suggest that 10 Hz GPS devices are an acceptable tool for detecting these actions at lower intensities (Varley, Fairweather, & Aughey, 2012; Cummins et al., 2013), there is some discrepancy in the literature. Varley, Fairweather and Aughey, (2012) assessed the reliability and validity of 10 Hz GPS units to quantify acceleration and deceleration in comparison to a laser device sampling at 2000 Hz and reported that the GPS demonstrated acceptable validity for accelerations in comparison to the laser (bias, -3.6 – -2.1%; CV, 3.6 – 5.9%). Although, during deceleration activities, the validity was lower (bias, 8.9%; CV, 11.3%). Here, the inter-unit reliability was lower for acceleration (CV, 1.9 – 4.3%) than deceleration (CV, 6.0%), but both were deemed acceptable. Akenhead et al. (2014) reported that both the validity and reliability of 10 Hz GPS for the measurement of instantaneous velocity is inversely related to acceleration intensity, particularly during accelerations of over 4 $m \cdot s^{-2}$. This is supported by a more recent study by Thornton et al. (2018), who compared the inter-unit reliability of 3 different 10 Hz GPS units (GPSports EVO, STATSports APEX and Catapult S5). The researchers investigated the variation between manufacturers by performing the same team sport simulation session with the units attached to a sled. The inter-unit reliability for most metrics was good (CV = <5%), with total distance, distance covered at various speed thresholds, and maximal speed exhibiting the best reliability. However, when using defined thresholds, acceleration and deceleration metrics exhibited the lowest reliability, particularly moderate decelerations, with CV values ranging from ~5 – 73%. Moreover, there were substantial differences between manufacturers, particularly for threshold-based acceleration and deceleration variables. The inter-unit reliability of most movements measured was deemed as good, suggesting that practitioners can have confidence within systems. However, there were substantial differences between manufacturer outputs despite all possessing the same sampling rate. Therefore, it is not recommended to use multiple systems interchangeably or compare data between separate GPS devices of the same model (Thornton et al., 2019).

2.4.5 Reliability and validity of accelerometry in sport

Through the integration of the GPS module with a tri-axial accelerometer (Figure 7), quantification of acceleration data across all three planes of movement (anterior, posterior, and lateral directions) is possible. Tri-axial accelerometers have been traditionally used in physical activity research as an indirect marker of energy expenditure in free-living conditions (Halsey, Shepard, & Wilson, 2011; Howe et al., 2009). In sporting scenarios, this technology has predominantly been used to produce a composite vector magnitude to determine the combined G-force as the sum of forces measured on each directional axis. Whilst many GPS providers have their own algorithms, the most common metric to summarise the tri-axial accelerometry data in previous literature is Playerload™ (Barrett, Midgley, & Lovell, 2014). Playerload™ is measured in arbitrary units based on data derived from three-dimensional measures of the instantaneous rate of change in acceleration (Figure 8). Whilst external load is still commonly determined by measuring the distances covered in a variety of locomotor classifications (Rampinini et al., 2015), tri-axial accelerometry has been utilised as a measure to quantify the mechanical stress common to team sports, such as abrupt changes in velocity and direction, jumping, or body contacts (Cummins et al., 2013; Varley & Aughey, 2013).

$$\text{Plyr. Ld(acc)}_{t=n} = \sum_{t=0}^{t=n} \sqrt{\left(\left(fwd_{t=i+1} - fwd_{t=i}\right)^2 + \left(side_{t=i+1} - side_{t=i}\right)^2 + \left(up_{t=i+1} - up_{t=i}\right)^2\right)}$$

$$\text{for } t = 0, 0.01, 0.02, 0.03 \ldots n$$

Figure 8. The vector equation used to calculate Playerload™ from tri-axial accelerometery data.

The utility of Playerload™ as a training load marker in soccer has been compared against established measures of both external load and internal load. In 15 professional soccer players over 97 training sessions, Scott et al. (2013) found significant relationships between two different methods of collecting RPE (CR10 and CR100) and Playerload™ ($r^2 = 0.80 – 0.83$). In addition, Boyd, Ball and Aughey (2011) assessed both inter and intra-unit reliability of

Playerload^{TM} in both laboratory (oscillating hydraulic testing machine) and field conditions (AFL matches) and reported that it held acceptable reliability in both conditions (CV, 0.91% – 1.9%; smallest worthwhile difference [SWD], 5.88%). The noise (i.e., CV) produced by the accelerometers was lower than the signal (i.e., SWD), suggesting that accelerometers can detect changes or differences in movement demands during AFL (Table 6; Boyd, Ball, & Aughey, 2011). Barrett, Midgley, and Lovell (2014) used a standardised incremental treadmill test and collected physiological (VO_2, HR) and Playerload^{TM} via a GPS unit positioned at the scapulae (industry-standard) and the centre of mass (COM; criterion). *Moderate* to *high* test-retest reliability was observed for total Playerload^{TM} and its individual planes of motion at both unit locations (ICC, 0.80 – 0.97; CV, 4.2 – 14.8%). However, wearing the GPS unit at the scapulae under-estimated Playerload^{TM} by 15.7% (± 9.7%) in comparison to the COM and the metric was not sensitive to the subtle expected changes in running kinematics with increased running speed. Nonetheless, the convergent validity of Playerload^{TM} was determined here with nearly perfect within-subject correlations with measures of internal load (i.e., HR). Furthermore, the relationship between Playerload^{TM} and internal load was not influenced by the unit position (scapulae vs COM). However, the authors observed high between-subject variability suggesting that caution should be used when making comparisons between individuals (Table 6; Barrett, Midgley, & Lovell, 2014). This is supported by Scott et al. (2015) who indicated that intra-unit reliability is better than inter-unit reliability for this metric. Consequently, in unison with other GPS derived metrics, it is recommended that the same device is consistently used by an individual player to facilitate comparisons between sessions or changes over time. A summary of the key studies that have assessed the reliability and validity of accelerometry in sport is presented in Table 6.

Table 6. Summary of key studies that have assessed the reliability and validity of accelerometry variables in sport.

Study	Aim	Methods	Results	Conclusions
Boyd, Ball, & Aughey (2011)	Assess the reliability of triaxial accelerometers as a measure of physical activity in team sports.	- 8 accelerometers (Catapult MinimaxX 2.0) attached to a hydraulic testing machine and oscillated over two protocols (0.5g and 3.0g) to assess within- and between device reliability. - Secondly, 10 players were instrumented with two accelerometers during AFL matches.	- Laboratory: Within- (Dynamic: CV 0.91 to 1.05%; Static: CV 1.01%) and between-device (Dynamic: CV 1.02 to 1.04%; Static: CV 1.10%) reliability was acceptable across each test. - Field: The between-device reliability of accelerometers during AFL matches was also acceptable (CV 1.9%). The SWD was 5.88%.	- The reliability of the MinimaxX accelerometer is acceptable both within and between devices under controlled laboratory conditions, and between devices during field testing. - MinimaxX accelerometers can be confidently utilized as a reliable tool to measure physical activity in team sports across multiple players and repeated bouts of activity.
Barrett, Midgley, & Lovell (2014)	establish the test-retest reliability and convergent validity of PlayerLoad™ (triaxial-accelerometer data) during a standardized bout of treadmill running.	- 44 team-sport players performed 2 standardized incremental treadmill running tests (7 – 16 $km{\cdot}h^{-1}$) 7 days apart. - VO_2, HR and Playerload™ (PL) measured as both scapulae and COM.	- Moderate to high reliability was observed for PL and its individual planes (ICC, .80-.97; CV, 4.2-14.8%) - Between-subject correlations between PL and VO_2, and between PL and HR were trivial to moderate (r = -0.43 to 0.33), whereas within-subject correlations were nearly perfect (r = 0.92 – 0.98).	-PL had a moderate to high degree of test-retest reliability and demonstrated convergent validity with measures of exercise intensity on an individual basis. - caution should be applied in making between-athletes contrasts in loading and when using recordings from the scapulae to identify lower-limb movement patterns.
Nicolella et al. (2018)	Intra and inter-device accuracy and reliability of the 100 Hz accelerometer embedded in athlete tracking devices (Catapult OptimEye S5).	- 19 accelerometers mounted to an aluminium bracket, bolted directly to an electrodynamic shaker table. - Subjected to oscillations in 3 planes of motion (X, Y, Z axis) at four levels of acceleration (0.1g, 0.5g, 1.0g and 3.0g). - Peak acceleration and Catapult Playerload™ compared.	- GPS devices demonstrated excellent intra-device reliability and mixed inter-device reliability. - Differences were found between devices for mean peak accelerations and Playerload™ for each direction and level of acceleration.	- Results emphasize the need for industry wide standards in reporting validity, reliability, and the magnitude of measurement errors. - Recommended that device reliability and accuracy are periodically quantified.

Abbreviations: GPS, global positioning system; g, g-force; CV, coefficient of variation; SWD, smallest worthwhile difference; VO_2, oxygen uptake; HR, heart rate; ICC, intraclass correlation coefficient; CV, coefficient of variation; COM, centre of mass.

2.4.6 Speed thresholds

As locomotion in team sport is performed throughout the full range of an individual's speed capability, the need for this to be categorised into thresholds (also called 'zones' or 'bands') is necessary. As these thresholds are generally customisable within GPS software, researchers have typically defined arbitrary thresholds to summarise the distance covered or time spent within different zones. Traditionally, these were broken down into four subjective categories: walking, jogging, striding, and sprinting (Gabbett & Mulvey, 2008). Some authors opted to simplify these into 'low', 'moderate', 'high' and 'very-high' intensity running categories (Coutts & Duffield, 2010). More recently, these thresholds have expanded into 6 – 8 activity bands, with the lower zones (e.g., 1 – 3) representing less intense actions and the upper zones (e.g., 4 – 6) representing a more intense action (Table 7) (Cummins et al., 2013). Having user-defined bands is beneficial when considering that speed capability will vary across different ages, sports, and levels of competition. However, it can make comparisons between and within sports challenging when shared bands are not used. An early review by Cummins et al. (2013) highlighted the importance of the consistency of speed bands and activity pattern definitions within a sport, as this facilitates precise comparison of performance between players, teams, playing levels, and seasons. Some researchers have advocated the use of individualised velocity zones based on a player's maximum velocity (Abt & Lovell, 2009; Reardon et al., 2015). The rationale for this is that as some athletes are inherently faster than others, therefore the speed at which they begin to run at high intensity differs. Whilst individual speed thresholds have been suggested to provide a more accurate indicator of individual effort (Reardon et al., 2015), they do not consider that the acceleration ability of each athlete may differ. In addition, having global speed thresholds is likely to be superior for comparison between teams and athletes (Reardon et al., 2015). Table 7 highlights the variation in velocity zones and the descriptive terminology used within soccer-specific literature.

Table 7. Classification of speed categories in previous soccer literature.

Study	Band 1 **Description; Speed ($km \cdot h^{-1}$)**	Band 2 **Description; Speed ($km \cdot h^{-1}$)**	Band 3 **Description; Speed ($km \cdot h^{-1}$)**	Band 4 **Description; Speed ($km \cdot h^{-1}$)**	Band 5 **Description; Speed ($km \cdot h^{-1}$)**	Band 6 **Description; Speed ($km \cdot h^{-1}$)**
Barbero-Alvarez et al. (2008)	Standing/stop; 0.0 – 0.5 $km \cdot h^{-1}$	Walk; 0.5 – 3.0 $km \cdot h^{-1}$	Low-intensity running; 3.0 – 8.0 $km \cdot h^{-1}$	Medium-intensity running; 8.0 – 13.0 $km \cdot h^{-1}$	High-intensity running; 13.0 – 18.0 $km \cdot h^{-1}$	Sprinting; >18.0 $km \cdot h^{-1}$
Bradley et al. (2009)	Standing; 0.0 – 0.6 $km \cdot h^{-1}$	Walking; 0.7 – 7.1 $km \cdot h^{-1}$	Jogging; 7.2 – 14.4 $km \cdot h^{-1}$	Running; 14.4 – 19.8 $km \cdot h^{-1}$	High-speed running; 19.8 – 25.2 $km \cdot h^{-1}$	Sprinting; > 25.2 $km \cdot h^{-1}$
Hill-Haas et al. (2009c)	Standing/stop; 0.0 – 0.4 $km \cdot h^{-1}$	-	-	Jogging; 7.9 – 13.0 $km \cdot h^{-1}$	Cruising; 13.0 – 18.0 $km \cdot h^{-1}$	Sprinting; >18.0 $km \cdot h^{-1}$
Castagna, Impellizzeri, & Cecchini (2009)	Standing; 0.0 – 0.4 $km \cdot h^{-1}$	Walking; 0.4 – 3.0 $km \cdot h^{-1}$	Jogging; 3.0 – 8.0 $km \cdot h^{-1}$	Medium-intensity running; 8.0 – 13.0 $km \cdot h^{-1}$	High-intensity running; 13.0 – 18.0 $km \cdot h^{-1}$	Sprinting; > 18.0 $km \cdot h^{-1}$
Casamichana & Castellano (2010)	Stationary-walking; 0 – 4.0$km \cdot h^{-1}$	-	Jogging; 4.0 – 7.0 $km \cdot h^{-1}$	Quick-running; 7.0 – 13.0 $km \cdot h^{-1}$	High-intensity running; 13.0 – 17.9 $km \cdot h^{-1}$	Sprinting; > 18.0 $km \cdot h^{-1}$
Buchheit et al. (2010)	-	-	Low-intensity running; <13.0 $km \cdot h^{-1}$	High-intensity running; 13.0 – 16.0 $km \cdot h^{-1}$	Very-high-intensity running; 16.0 – 19.0 $km \cdot h^{-1}$	Sprinting; > 19.0 $km \cdot h^{-1}$

Harley et al. (2010)	-	-	-	High-speed running; 14.4 – 19.8 km·h^{-1}	Very high-speed running; 19.8 – 25.2 km·h^{-1}	Sprint; >25.2 km·h^{-1}
Gaudino et al. (2013)	-	-	-	High-speed; 14.4 – 19.8 km·h^{-1}	Very high-speed; 19.8 – 25.2 km·h^{-1}	Maximal speed; >25.2 km·h^{-1}
Scott et al. (2013)	-	-	-	High-speed running; 14.4 – 19.8 km·h^{-1}	Very high-speed; running >19.8 km·h^{-1}	
Anderson et al. (2016)	Standing; 0 – 0.7 km·h^{-1}	Walking; 0.7 – 7.2 km·h^{-1}	Jogging; 7.2 – 14.4 km·h^{-1}	Running; 14.4 – 19.8 km·h^{-1}	High-speed running; 19.8 – 25.2 km·h^{-1}	Sprinting; >25.2 km·h^{-1}
Ehrmann et al. (2016)	-	-	-	High-intensity running; 14.4 – 19.8 km·h^{-1}	Very high-intensity running; >19.8 km·h^{-1}	-
Owen et al. (2017b)	-	-	-	-	High-speed running; 19.8 – 25.2 km·h^{-1}	Sprinting; > 25.2 km·h^{-1}
Lacome et al. (2018)	-	-	-	High-speed running; >14.4 km·h^{-1}	-	-

2.4.7 Software updates

Another consideration when using GPS technology is the effects of software updates. Buchheit et al., (2014a) reported substantial differences in GPS outputs after a software update. Whilst the update did not substantially affect distance or speed outputs, the prevalence of accelerations and decelerations within the same thresholds were altered by up to 56%. Therefore, it is important to consider the impact of software updates or avoid them when making longitudinal comparisons between GPS data.

2.4.8 Global positioning systems summary

On the evidence in the literature, it seems that GPS devices sampling at 10 Hz provide reliable and valid measures of total distance, HSR, and accelerometry demands in sport-specific movements. However, caution should be used with certain metrics, such as high-intensity accelerations and decelerations, as the reliability and validity have been questioned in some studies (Akenhead et al., 2014; Buchheit et al., 2014a; Thornton et al., 2019). Furthermore, devices with different sampling frequencies and from different manufacturers should not be used interchangeably, and the same device should be worn by the same player over time (Barrett et al., 2014; Scott et al., 2015; Thornton et al., 2019). Whilst quantifying the exercise 'dose' is clearly important in understanding the physical demands of training and competition, the ability to monitor the consequential responses of the athlete is also imperative. Therefore, the following sections of this review will discuss neuromuscular fatigue (section 2.5) before addressing other monitoring methods described in previous literature (section 2.7).

2.5 NEUROMUSCULAR FATIGUE

Due to training and competition demands, athletes will experience a continuous cycle of fatigue, recovery, and adaptation. Accordingly, an understanding of the mechanisms that underpin these, in addition to being able to monitor them appropriately is essential in determining appropriate training loads to optimise performance (Fowles, 2006). One of the most characterised responses to exercise is a temporary loss of performance as a result of fatigue, and many different models have been proposed to describe the causes and effects of fatigue (Abbiss & Laursen, 2005). Whilst fatigue is a complex phenomenon and is likely multi-factorial in nature and very dependent on the task being performed, for the purpose of this review and the subsequent experimental chapters, there will be a primary focus on the neuromuscular fatigue model.

There is a general agreement within the literature that neuromuscular fatigue can be defined as an exercise-induced decline in the maximal voluntary force or power produced by a muscle or muscle group, despite increases in perception of effort (Bigland-Ritchie & Woods, 1984; Gandevia, 2001; St Clair Gibson, Lambert, & Noakes, 2001). Neuromuscular fatigue is typically subdivided into categories depending on where in the activation-contraction chain the breakdown or change in force-generating capacity occurs (Abbiss & Laursen, 2005; Paasuke, Ereline, & Gapeyeva, 1999). Mechanisms with origins at or distal to the neuromuscular junction (NMJ) are defined as peripheral fatigue, whereas those that occur in the brain and spinal cord (i.e., central nervous system [CNS]) are referred to as central fatigue. Most researchers agree that neuromuscular fatigue can potentially develop at any, or in multiple locations during the activation-contraction chain (Bigland-Ritchie & Woods, 1984; MacLaren et al., 1989). Moreover, the specific mechanisms of neuromuscular fatigue are influenced by the type of muscle contraction, volume and intensity of the exercise, the rest period between contractions, and the characteristics of the musculature involved (Bosco, Luhtanen, & Komi, 1983; Collins et al., 2018).

2.5.1 Mechanisms of central fatigue

Several mechanisms of fatigue may originate proximal to the NMJ or within the CNS. Central fatigue is defined as a progressive reduction in voluntary activation (VA) of the muscle during exercise (Enoka & Stuart, 1992; Gandevia, 2001). A common technique to determine the level of VA (or neural drive) is through the interpolated twitch technique (ITT), whereby a supramaximal electrical stimulation of the motor nerve is applied during a maximum voluntary contraction (MVC) (Belanger & McComas, 1981; Taylor & Gandevia, 2008). If extra force can be evoked by motor nerve stimulation during an MVC then that indicates that not all the motor units were voluntarily recruited or were not discharging at rates high enough to produce fully fused contractions (Merton, 1954; Belanger & McComas, 1981; Herbert & Gandevia, 1999). An increase in this superimposed twitch indicates that central fatigue is present and that processes proximal to the site of motor nerve stimulation, at least in part, are contributing to a loss of force (Gandevia, 2001). Additionally, some central fatigue can be attributed to supraspinal mechanisms (Gandevia et al., 1996; Taylor, Todd, & Gandevia, 2006), and transcranial magnetic stimulation (TMS) of the motor cortex can identify mechanisms of fatigue that occur within the brain (Todd, Taylor, & Gandevia, 2016). Increases in increments of force evoked by TMS during MVC demonstrates that some of the loss of force can be attributed to suboptimal output from the motor cortex (Todd, Taylor, & Gandevia, 2016). Therefore, an increase in a superimposed twitch elicited by cortical stimulation is a classical marker of supraspinal fatigue (Taylor et al., 2016).

The use of MVCs has advantages for the study of central fatigue as opposed to submaximal contractions, although these processes are likely to occur in weak as well as strong contractions (Taylor & Gandevia, 2008). Firstly, during an MVC, a superimposed twitch represents a failure of the CNS to drive the muscle maximally, whereas during submaximal tasks there is no benchmark for optimum performance (Taylor & Gandevia, 2008). Secondly, the task for the CNS during an MVC is assumed to be maximal throughout the exercise, with the aim of driving all the motor units to produce maximum force. In comparison, a submaximal task allows the CNS to compensate for muscle failure by increasing neural drive (Bigland-Ritchie, Cafarelli, & Vollestad, 1986; Dorfman, Howard, & McGill, 1990). For these reasons, it is problematic to test the influence of central processes on the performance of a submaximal task, when both voluntary drive to the motor neurons and the force-generating capacity of the muscle is continuously changing (Taylor & Gandevia, 2008). It should also be acknowledged that potential limitations have been highlighted with the use of MVCs to assess central fatigue, as additional factors may influence VA, such as hydration status, psychological, and environmental factors (Abbiss & Laursen, 2005).

Whilst considerable neuromuscular fatigue can be attributed to mechanisms distal to the motor nerve (peripheral fatigue), clear contributions to loss of force can be attributed to spinal and supraspinal factors. This has been demonstrated during MVCs performed continuously, intermittently or superimposed onto submaximal contractions (Boerio et al., 2005; Taylor & Gandevia, 2008). Previous authors have proposed that central fatigue can account for ~10 – 25% of the reductions in maximal force production during single-joint exercise (e.g., elbow flexion) (Taylor & Gandevia, 2008; Gandevia, 2001). In addition, considerable central fatigue has been shown in response to multiple-joint and whole-body exercises involving larger muscle mass. For example, significant losses of VA have been reported after soccer matches (Rampinini et al., 2011; Brownstein et al., 2017), soccer match simulations (Marshall et al., 2014; Thomas et al., 2017; Goodall et al., 2017), prolonged locomotor exercise (Place et al., 2004; Millet et al., 2002, Millet et al., 2003; Thomas et al., 2015), repeat sprint exercise (Goodall et al., 2015; Pearcey et al., 2015; Pearcey et al., 2016), high-intensity short-duration exercise (Husmann et al., 2016), and also heavy resistance exercise (Kraemer & Ratamess, 2004a; Walker et al., 2012).

Several mechanisms have been proposed to explain central fatigue. Although the underlying mechanisms are complex, and the precise origins are inconclusive, slowing of motor neuron firing rates have been shown in both sustained and repeated maximal contractions (Bigland-Ritchie et al., 1983; Bigland-Ritchie et al, 1992; Marsden, Meadows, & Merton, 1983; Rubinstein & Kamen, 2005; Gandevia, 1992; Taylor & Gandevia, 2008). Accordingly, the mechanisms that contribute to decreased motor neuron firing rates are fundamental to central fatigue (Taylor & Gandevia, 2008). In simple terms, three possible mechanisms related to the slowing of motor neurons have been identified; (a) decreased excitatory input, (b) increased inhibitory input and (c) decreased motor neuron responsiveness (Taylor & Gandevia, 2008). It is likely that all three mechanisms, in part, contribute to central fatigue, which will be discussed in the following sections.

2.5.1.1 Decreased excitatory input

Changes in the concentrations of neurotransmitters in the brain have been linked to central fatigue (Abbiss & Laursen, 2005; Taylor et al., 2016). In particular, the monoamines serotonin, dopamine and noradrenaline are thought to play a key role in signal transduction between neurons, which may influence the rate of central neural drive, the excitability, and the recruitment of skeletal muscle (Davis, 1995; Davis & Bailey, 1997; Davis, Alderson, & Welsh, 2000). The most prominent theory, first proposed by Newsholme and co-workers (1987), suggests that exercise-induced increases in serotonin may have a negative impact on arousal and mood state, which in turn may increase the perception of effort during exercise (Newsholme, Acworth, & Blomstrand, 1987). More specifically, the entry of unbound tryptophan, a precursor to serotonin, into the CNS across the blood-brain barrier is favoured during exercise due to muscle use of BCAA and elevated free fatty acid (FFA) (Blomstrand, Celsing, & Newsholme, 1988). This theory proposes that a greater concentration of FFA results in less competition for tryptophan in binding to albumin, along with a higher ratio of unbound tryptophan to BCAA, which results in a higher net gain of free tryptophan transport into the brain, thus resulting in increased serotonin concentrations (Meeusen et al., 2006b; Roelands, & Meeusen, 2010). Several studies have challenged this hypothesis by attempting to manipulate performance with nutritional and pharmacological interventions, with contrasting results (Davis & Bailey, 1997; Davis, Alderson, & Welsh, 2000; Roelands & Meeusen, 2010). Whilst findings in animal studies provide convincing evidence for the role of serotonin in the onset of fatigue (Bailey, Davis, & Ahlborn, 1992; Bailey, Davis, & Ahlborn, 1993), evidence in humans is less convincing (Pannier, Bouckaert, Lefebvre, 1995; Meeusen et al., 2001; Roelands et al., 2009). The contrasting findings in the literature are likely a result of the complexity of the serotonin neurotransmitter system, as many different receptors and subtypes have been identified, each with different functions and interactions (Taylor et al., 2016). The lack of consensus amongst studies that have tried to manipulate the neurotransmitter system suggests that serotonin is not the key factor in the development of central fatigue. However, it may play a role in combination with additional mechanisms.

2.5.1.2 Decreased responsiveness of the motor neurons

Another proposed mechanism is that repetitive activation of motor neurons may lead to a reduction in their excitability to synaptic input (Taylor et al., 2016). This process is known as spike-frequency adaptation (or late adaptation) and can be demonstrated when motor neurons are given a maintained input by intracellular current injection (Kernell & Monster, 1982; Spielmann et al., 1993; Sawczuk, Powers, & Binder, 1997; Gorman et al., 2005). Initially, the motor neurons fire repetitively, but after some time, some motor neurons slow their firing rate and others completely stop (Spielmann et al., 1993; Peters & Fuglevand, 1999). Evidence for this is in human studies is limited (Nordstrom et al., 2007). However, if participants are given feedback that allows them to voluntarily activate a single motor unit at a constant rate over a given timeframe, the longer the unit is active the more drive is required to maintain its firing rate (Johnson et al., 2004). This implies that the target motor neuron requires progressively more descending drive to maintain the same output (Johnson et al., 2004). The motor neuron responsiveness has been shown to recover within ~1 – 2-min of firing (Taylor & Gandevia, 2008), and is thought to be influenced by intrinsic changes in the motor neuron properties related to both ionotropic and metabotropic effects (Taylor et al., 2016).

2.5.1.3 Increased inhibitory input

Peripheral feedback from small-diameter muscle afferents (specifically type III/IV) may also facilitate central fatigue by providing inhibitory feedback to the regulation of central motor drive, which decreases VA during exercise (Bigland-Ritchie, Cafarelli, & Vøllestad, 1986; Gandevia et al., 1996.; Gandevia, 2001; Taylor & Gandevia, 2008; Amann et al., 2009). Type III and IV afferents are sensitive to mechanical strain and chemical stimuli, causing some to increase firing rate with the accumulation of metabolites in fatigued and damaged muscle (Mense, 1977; Rotto & Kaufman, 1988; Sinoway et al., 1993; Li & Sinoway, 2002). This has been demonstrated by Gandevia et al. (1996) during maximal isometric contractions of a single joint. The authors initially reported that the output from motor neurons and VA was found to progressively decrease during a 2-min MVC of the elbow flexors (i.e., biceps brachii), yet recover to baseline levels within minutes after the cessation of exercise. However, in another trial, a sphygmomanometer cuff was inflated around the upper arm at the end of the MVC in order to restrict blood flow, accumulate metabolites and maintain the firing of type III and IV afferents. In this trial, the motor neuron output and VA remained low and did not recover until the cuff was deflated, circulation restored, and type III/IV mediated feedback recovered (Gandevia et al., 1996).

The inhibitory effect of type III/IV afferents on central drive has also been demonstrated during high-intensity endurance exercise by Amann et al. (2009). In this study, eight cyclists performed three 5 km time trials with either pharmacologically blocked type III/IV muscle afferents (via lumbar intrathecal fentanyl), a placebo (saline injection) or under control conditions. The authors reported that during the first half (2.5 km) of the cycle during the fentanyl trial, quadriceps electromyography (EMG) and power output were 12 ± 3% and 6 ± 2% higher than the placebo trial respectively, suggesting that the blocked group III and IV muscle afferents led to an increased central motor drive. However, during the second half of the cycle, quadriceps EMG was similar between trials, and power output was 11 ± 2% lower during the fentanyl trial compared to the placebo. This suggests that the metabolic by-products accumulated during the first half of the cycle were not ‘sensed’ by the CNS during the fentanyl trial, resulting in an excess of central drive and power output that would normally be chosen by the athlete as a pacing strategy, thereby creating a greater accumulation of peripheral fatigue during the second 2.5 km of the cycle (Amann et al., 2009).

Interestingly, the inhibitory influence of type III and IV muscle afferents on motor neuron output is not only specific to the working muscle group but can also cross over to affect muscle groups not directly involved in the locomotor task. During a cycling protocol at 80% of peak power output to fatigue, Sidhu et al. (2014) compared cortical VA (via TMS) during MVC of the elbow flexors under control conditions to a trial with impaired feedback from locomotor afferents (via lumbar intrathecal fentanyl). Under control conditions, elbow flexor MVC and cortical VA were significantly reduced from pre- to post-exercise (Figure 9 A & B). By contrast, under the fentanyl condition, elbow flexor MVC and VA remained unchanged. Therefore, in the presence of cycling-induced lower limb fatigue, group III/IV locomotor muscle afferents facilitate supraspinal fatigue in remote muscles not involved in the exercise (Figure 9 A & B).

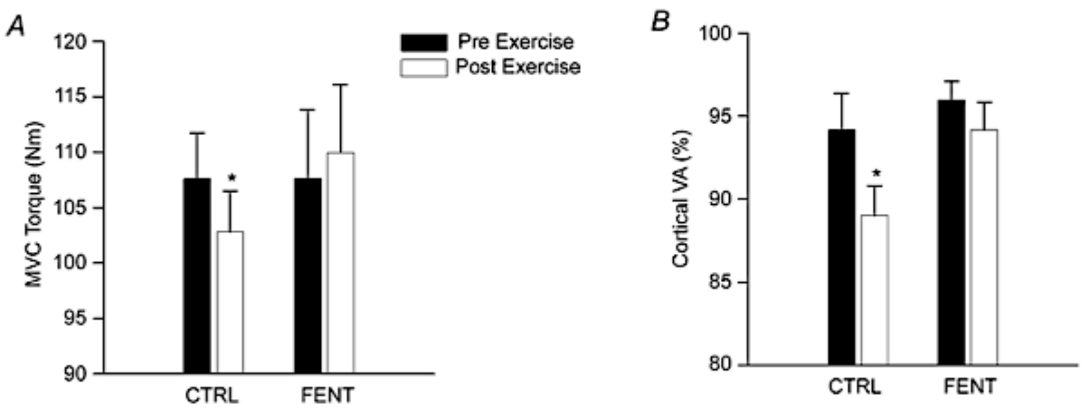

Figure 9 (A & B). Elbow flexor maximum voluntary contraction (MVC) torque and cortical voluntary activation (VA) pre and post cycling protocol to fatigue in both control (CTRL) and fentanyl (FENT) trials. Reproduced from Sidhu et al. (2014).

2.5.2 Mechanisms of peripheral fatigue

An alternative rationale for neuromuscular fatigue during exercise is that force-reducing mechanisms occur at, or distal to the NMJ. Peripheral fatigue is generally measured as a reduction in evoked muscle force production in response to supramaximal electrical stimulations delivered to the motor nerve of relaxed muscles (Verges et al., 2009; Millet et al., 2011; Fowles, 2006; Schillings, Stegeman, & Zwarts, 2005). The force-reducing mechanisms may include changes in action potentiation propagation, E-C coupling, cross-bridge cycling, substrate depletion and metabolite accumulation (Fitts, 1994). Peripheral fatigue can be further subdivided into high-frequency fatigue (HFF) or low-frequency fatigue (LFF) (Abiss & Laursen, 2005).

2.5.2.1 Low-frequency fatigue

Directly within the muscle fibre, it seems that dysfunction occurs in the E-C coupling mechanism, which is seen to occur with repeated low-frequency stimulation (10 – 20 Hz). This has been labelled LFF and requires more central drive to produce the same levels of force (Abiss & Laursen, 2005). The LFF concept, also described as the 'Peripheral Failure Theory' (Figure 10; Abiss & Laursen, 2005), has been described as multifactorial fatigue resulting from moderate to high-force high-intensity exercise involving repetitive eccentric or stretch-shortening cycle (SSC) activities (Fowles, 2006; Lattier et al., 2004; Strojnik & Komi, 2000). As discussed in the previous chapters of this review, performance in soccer and team sport, in general, requires the regular performance of activities such as sprinting, accelerating, and decelerating, all of which involve repetitive high-force SSC actions. Therefore, it is very likely that LFF has a significant contribution to the reduced neuromuscular function seen immediately post soccer activity, and in the hours and days that follow (Nedelec et al., 2012; Andersson et al., 2008; Ispirlidis et al., 2008; Fatouros et al., 2010; Magalhães et al., 2010; Rampinini et al., 2011).

The LFF theory suggests that decreased force production of skeletal muscle is due to an impairment in the E-C coupling mechanism (Figure 10). This theory proposes that a combination of metabolite accumulation (H^+, ammonia and inorganic phosphate [Pi]), energy substrate depletion (adenosine triphosphate [ATP], PCr, and glycogen) and a decrease in intracellular Ca^{2+} concentration have been suggested to contribute to the development of LFF (Binder-Macleod & Russ, 1999; Byrne et al., 2004; Allen, Lamb, & Westerblad, 2008). More specifically, changes in the coupling mechanism between action potential and contractile proteins, or reduced Ca^{2+} release from the sarcoplasmic reticulum (SR), resulting in decreased Ca^{2+} binding to troponin C and subsequent impairment of actin-myosin interactions during cross-bridge cycling (Binder-Macleod & Russ, 1999; Abbiss & Laursen 2005; Drinkwater, Lane, & Cannon, 2009). The characteristically slow recovery rate of force-generating ability that is associated with LFF may be an important consideration when monitoring the neuromuscular fatigue responses to team sport activity.

2.5.2.2 High-frequency fatigue

Another potential mechanism of neuromuscular fatigue is HFF, also described as the 'Neuromuscular Propagation Failure Theory' (Figure 10; Abiss & Laursen, 2005; McLellan, 2010), can be demonstrated when force production of motor neurons decreases when stimulated at frequencies ≥50 Hz. This theory suggests that the force-generating ability of a muscle is limited by its response to an electrical stimulus (Lepers et al., 2002; Walton et al., 2002; Abiss & Laursen, 2005). The mechanism of HFF is thought to occur at the level of the sarcolemma or alpha motor neuron (Abiss & Laursen, 2005). More precisely, increased Na^+ and reduced K^+ transmembrane gradients have been attributed to insufficient Na^+/ K^+ pump activation (Green, 1997; Nielsen & Clausen, 2000). This changes the intracellular Na^+ and K^+ and decreases the action potential (M-wave) propagation into the T-tubule system, resulting in reduced Ca^{2+} release from the SR and a consequent reduction in the activation of contractile elements involved in force generation (Enoka & Stuart, 1992; Green, 1997; Abiss & Laursen, 2005). Significant HFF has been reported after metabolically demanding tasks such as repeat sprint running (Perrey et al., 2010), and maximal intensity SSC actions (Jereb & Strojnik, 2001; Strojnik and Komi, 1998; Tomazin et al., 2008). Therefore, it is possible to theorise that performance of SSGs may produce a similar response.

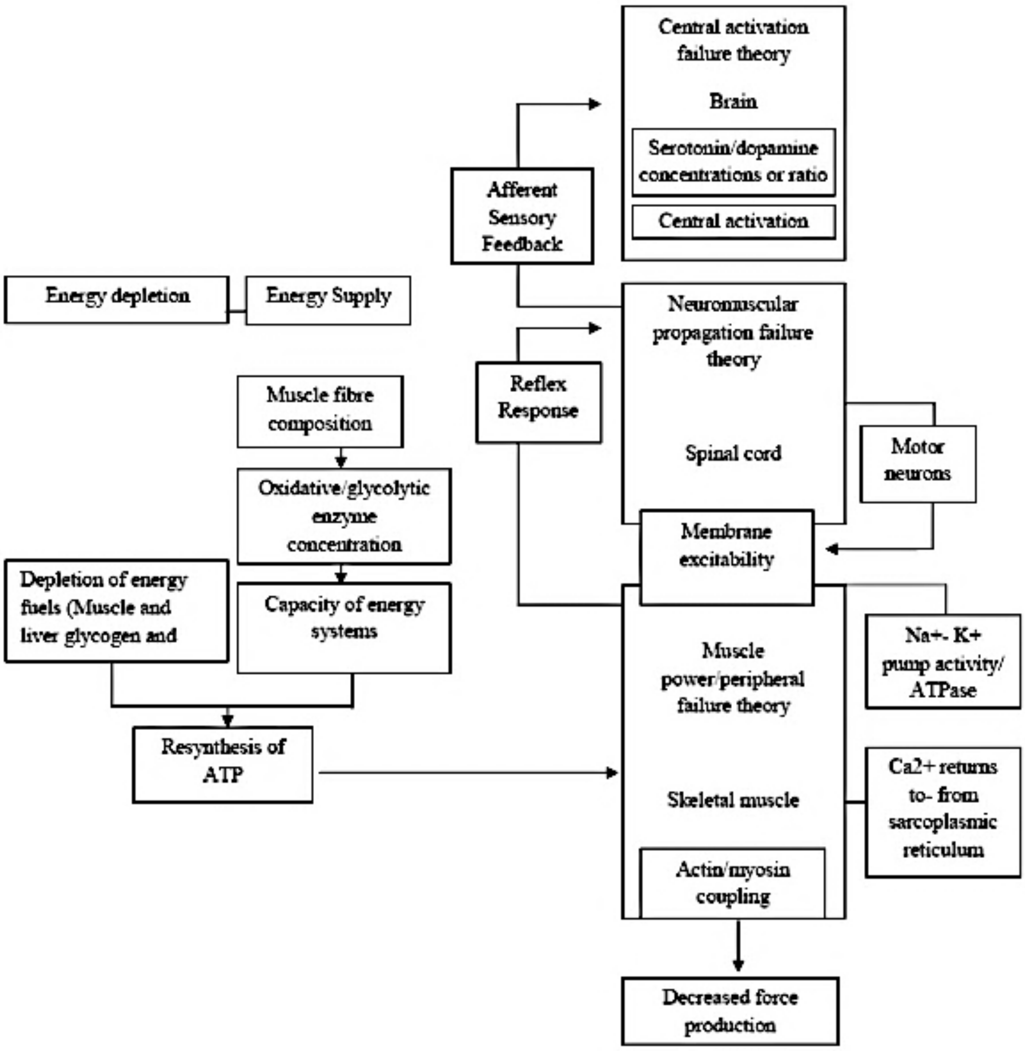

Figure 10. The Neuromuscular Fatigue Model (reproduced from McLellan, 2010; adapted from Abbiss & Laursen, 2005).

2.5.3 Neuromuscular fatigue in soccer

Several studies have directly studied neuromuscular fatigue in soccer, after both simulated (Thomas et al., 2017; Goodall et al., 2017) and real (Rampinini et al., 2011; Brownstein et al., 2017) match play (Table 8). These studies have recruited a range of participants, from amateur (Goodall et al., 2017), semi-professional (Brownstein et al., 2017; Thomas et al., 2017), and professional (Rampinini et al., 2011) players. From the evidence presented in these studies, it is clear that the demands of soccer result in significant neuromuscular fatigue, which originates from both central and peripheral mechanisms. Together, these studies have reported immediate post-exercise declines in knee extensor MVC (range of study means; -20 – -11%), VA measured with motor nerve stimulation (range of study means; -15% – -7%), VA measured with TMS (range of study means; -15 – -5%), and potentiated twitch force (range of study means; -23 – -14%), which persist for up to 48 – 72 hours post-exercise (Table 8). These studies suggest that whilst central processes originating at the spinal and supraspinal level contribute significantly to the post-exercise declines in neuromuscular function, the typically slower recovery time course of peripheral indicators suggests that this primarily explains the delayed recovery in the days that follow (Rampinini et al., 2011; Thomas et al., 2017). Whilst the exact mechanisms responsible for the declines in VA are not elucidated in these studies, it is possible that the various biochemical changes (e.g., pH and K^+) during the game might stimulate the previously mentioned group III and IV muscle afferents, which may inhibit central drive (Gandevia, 2001). The peripheral fatigue noted is likely related to muscle damage and the subsequent inflammatory response, rather than processes within the CNS, which is supported by the large increases in creatine kinase (CK) concentrations in the days post-exercise (Rampinini et al., 2011; Thomas et al., 2017).

Another important finding in two of these studies (Thomas et al., 2017; Brownstein et al., 2017) was that vertical jump performance (i.e., CMJ height) showed a similar decline and subsequent recovery time course to other neuromuscular measurements, suggesting that this is a sensitive and practical marker of assessing the neuromuscular response to soccer activity. However, Brownstein et al. (2017) reported that subjective markers (i.e., perceived fatigue and muscle soreness) may show a delayed recovery in comparison to physical variables, reporting these markers to still be depressed at 72 hours post despite the recovery of physical variables. This divergent recovery of perceptual measures in comparison to measures of neuromuscular function emphasises the previously mentioned multi-factorial nature of neuromuscular fatigue.

This highlights the need for practitioners and researchers to consider a full battery of tests to gain a comprehensive understanding of the responses to the varied mechanical, metabolic and cognitive demands of soccer activity (Brownstein et al., 2017).

Table 8. Summary of the key studies that have directly assessed neuromuscular fatigue after soccer matches or match simulation protocols.

Study	Design	Results	Conclusions
Rampinini et al. (2011)	- 20 professional male players competed in a 90-min friendly match. - Pre, immediately post, 24 and 48h after the game, quadriceps MVC, VA, EMG activity, evocated contractile properties, muscle soreness, 40 m shuttle sprint and passing ability were measured.	- Immediate post-match declines in MVC (-11%), VA (-8%), EMG activity (-12%), mechanical responses to single and paired stimulations at 10 Hz (-8 – -9%), and sprint performance (-3%) occurred ($p < 0.001$) and returned to baseline by 48h ($p > 0.05$). - Perceived muscle soreness and CK were significantly elevated *(*$p < 0.001$) until 48h post-match. - Short passing ability was unchanged across all time points ($p > 0.05$).	- Match related fatigue is determined by a combination of central and peripheral factors. - A relationship exists between CNS indicators and declines in MVC and sprint performance. - Muscle soreness, damage, and inflammation are likely linked to peripheral fatigue. - Most variables that were negatively affected by match-play recovered by 48h post.
Thomas et al. (2017)	- 15 semi-professional male soccer players performed a battery of neuromuscular, physical, and perceptual tests before, and immediately, 24, 48 and 72h after a 90-min simulated soccer match. - Quadriceps MVC and twitch responses to electrical (femoral nerve) and TMS of the motor cortex during isometric contractions and at rest were measured to assess central (VA) and peripheral (potentiated twitch force) fatigue. - Responses to single and paired magnetic stimuli were assessed to quantify corticospinal excitability and short intracortical inhibition, respectively. - CMJ, reactive strength index, sprint performance, CK, perceived fatigue and muscle soreness were also assessed.	- MVC immediately decreased (-17%; $p < 0.001$) and was still below baseline at 72h (-3%; $p = 0.01$). - VA measured via femoral nerve immediately declined (-9%; $p < 0.001$), remained depressed at 48h (-2%; $p = 0.03$), and recovered by 72h post ($p > 0.05$). - VA quantified through TMS was reduced immediately (-10%; $p < 0.05$), remained depressed at 24h (-3%; $p < 0.05$), but recovered by 48h post. - Potentiated twitch force declined immediately (-14%; $p < 0.001$) and remained below baseline at 72h (-5%; $p = 0.01$). - Corticospinal excitability was reduced at 24h only (-5 – -6%; $p < 0.05$) and no change in intracortical inhibition was observed ($p > 0.05$). - CMJ height, reactive strength index, and self-report measures presented a similar recovery time course to other neuromuscular measures.	- Simulated soccer match play induced significant neuromuscular fatigue that was both central and peripheral in origin and persisted for up to 72h postexercise. - Central processes contribute significantly to the declines in neuromuscular function, but the magnitude and slower recovery of peripheral fatigue indicates that the resolution of muscle function primarily explains the delayed recovery after soccer activity. - The similar decline and the subsequent time course recovery of physical (CMJ and reactive strength index) and perceptual variables suggest these are appropriate tools to assess the recovery of neuromuscular function after soccer match play.

Brownstein et al. (2017)	- 16 semi-professional male soccer players performed a series of neuromuscular, physical, and perceptual tests at pre and immediately, 24, 48 and 72h post a 90-min competitive match. - MVC and twitch responses to electrical (femoral nerve) and TMS of the motor cortex during isometric knee extension and at rest were measured to assess CNS (VA) and muscle contractile (potentiated twitch force) function. - EMG responses of the rectus femoris to single- and paired-pulse TMS were used to assess corticospinal excitability and intracortical inhibition, respectively. - CMJ, reactive strength index, sprint performance, perceived fatigue and muscle soreness were also assessed.	- MVC force immediately declined (-14%, $p < 0.001$), remained below baseline at 48h (-4%, $p = 0.01$), before recovering by 72h. - VA measured through motor point stimulation immediately declined (-7%, $p < 0.001$), remained depressed at 24h (-5%, $p = 0.01$), and recovered at 48h. -VA measured via TMS reduced post-match (-5%; $p < 0.001$) and recovered at 24h post. - Potentiated twitch force was reduced post-match (-14%, $p < 0.001$), remained depressed at 24h (-6%, $p = 0.01$), and recovered by 48h. - No changes in corticospinal excitability or intracortical inhibition were noted. - CMJ height recovered by 48h whilst perceptions of fatigue persisted at 72h post.	- Competitive soccer match-play elicits substantial CNS and muscle function impairments which may require 48 – 72h to resolve - CMJ and reactive strength index showed a comparable recovery time course to markers of neuromuscular fatigue at a group level. - Practitioners should use a range of both subjective and objective measures when monitoring fatigue and recovery after soccer matches.
Goodall et al. (2017)	- 10 male amateur players performed 120-min of match simulation, replicating the demands of extra time. - Before, at 45-min (half-time), 90-min (full-time), and 120-min (extra-time), twitch responses to supramaximal femoral nerve and TMS were obtained from the knee extensors to assess neuromuscular fatigue. - Within 7 days of the first trial, a second 120-min match simulation was performed to assess the reproducibility of the fatigue response.	- At half-time, full-time, and extra-time, reductions in MVC (-11, -20, and -27%, respectively, $p \leq 0.01$), potentiated twitch force (-15, -23, and -23%, respectively, $p < 0.05$), VA measured with TMS (-11, -15, and -17%, respectively, $p \leq 0.01$), and VA (full-time, -15%; extra-time, -18%; $p \leq 0.01$) were evident. - Reliability values for MVC were good (CV, 6–11%; ICC, 0.83–0.94), moderate for motor nerve stimulation (CV, 5–18%; ICC, 0.63–0.89), and excellent for motor cortex stimulation (CV, 3–6%; ICC, 0.90–0.98).	- 90-min of simulated soccer elicits reductions in quadriceps force generating capabilities, and this fatigue is derived from a combination of both central and peripheral factors. - The added 30-min simulation of extra-time induced further fatigue that was primarily of central origin. - The measurements of fatigue were consistent when repeated within 7 days, with the most variable responses noted following extra-time.

Abbreviations: MVC, maximum voluntary contraction; EMG, electromyography; VA, voluntary activation; CK, creatine kinase; TMS, transcranial magnetic stimulation; CMJ, countermovement jump; CNS, central nervous system; CV, coefficient of variation; ICC, intraclass correlation coefficient.

One of the studies in this area by Goodall et al. (2017), obtained neuromuscular measurements within the time course of a soccer match simulation that was designed to replicate the demands of extra-time (i.e., 120-min). Measurements were taken through the course of the simulation, at 45, 90, and 120-min during the protocol. The authors reported that significant central and peripheral fatigue manifests as early as half-time (i.e., 45-min), before a progressive decline thereafter (i.e., 90 and 120-min). Furthermore, the added fatigue response in the additional 30-min of activity (between 90 and 120-min) was primarily explained by central mechanisms, as evidenced by a progressive decline in VA throughout the simulation (Table 8). This finding provides further evidence that central fatigue becomes progressively more limiting as the exercise duration extends, which has been noted in prolonged running (Thomas et al., 2015) and cycling (Place et al., 2004) activities. This could be an important consideration, as SSGs are typically performed over a shorter duration (e.g., <45-min) in comparison to match play (i.e., ≥90-min). Furthermore, this would suggest that practitioners should consider when in the training session each exercise is performed, as a progressive decline in VA could alter the fatigue and performance of the players in the latter stages of a training session when compared to the earlier stages.

Interestingly, the magnitude of immediate declines in neuromuscular function appears to be greater in the studies that investigated the responses to match simulations (Thomas et al., 2017; Goodall et al., 2017) in comparison to real matches (Rampinini et al., 2011; Brownstein et al., 2017). For example, after 90-mins of real match play, Rampinini et al. (2011) and Brownstein et al. (2017) reported average declines in quadriceps MVC of -11 and -14%, respectively. In comparison, after 90-min of soccer match simulation, Thomas et al. (2017) and Goodall et al. (2017) reported declines of -17 and -20%, respectively. These apparent differences in the immediate post-exercise changes may be related to the time at which the measures of neuromuscular function were taken, and due to the logistical constraints of performing a battery of tests with numerous players within a strict timeframe immediately after a match. For example, in the two studies which examined the responses to matches, measures were obtained at 40 minutes (Rampinini et al., 2011) and between 10 – 60 minutes (Brownstein et al., 2017) post-match. In contrast, due to the ability of the researchers to manipulate the start and the end times of each participant during the simulation protocols, the measurements were obtained within 2.5-min of the cessation of exercise (Thomas et al., 2017; Goodall et al., 2017). This difference in the proximity of measures to the cessation of exercise may allow the studies that adopted the simulated activity to capture the full extent of fatigue before it dissipated, which is an important consideration when examining the neuromuscular responses to exercise (Taylor et al., 1996; Taylor & Gandevia, 2008).

Another interesting factor is that the recovery time course of neuromuscular function appears to be faster following real match play, with the majority of variables returning to baseline by 48 – 72 hours post (Rampinini et al., 2011; Brownstein et al., 2017). In comparison, Thomas et al. (2017) reported that declines in neuromuscular function following match simulation remained unresolved at 72 hours post. One possible explanation for this could be due to the time in the season in which the studies were conducted. Namely, the study by Thomas et al. (2017) was conducted during the late off-season and early pre-season phase, whereas the studies by Rampinini et al. (2011) and Brownstein et al. (2017) were conducted during, and one week following the competitive season, respectively. Therefore, the players may have been in a better physical condition and more accustomed to the demands of soccer match play. Another important consideration is that whilst simulations reduce the inherent individual variability associated with actual match play, the self-paced nature of real matches requires players to adjust their movement to external stimuli, which varies greatly according to their positional differences. Therefore, it is possible that participants were less accustomed to the specific demands of the simulated protocol implemented by Thomas et al. (2017), which involves actions such as forced decelerations, which could result in greater muscle damage and possibly contribute to the delayed recovery of muscle function and fatigue markers. Whilst simulation protocols have their benefits in the study of neuromuscular fatigue and are carefully designed to replicate the physiological demands of matches, it has been suggested that many of the cognitive aspects (e.g., decision making, reacting, and anticipating) and the diverse range of mechanical and neuromuscular stimuli during real match play may not be fully replicated (Magalhães et al., 2010). Nevertheless, taken together these studies present important information and offer insight into the mechanisms that may explain the neuromuscular response to soccer-specific exercise.

2.5.4 Summary of neuromuscular fatigue

The complex phenomenon of neuromuscular fatigue can be defined as an exercise-induced decline in the maximal voluntary force or power produced by a muscle or muscle group, despite increases in perception of effort (Bigland-Ritchie & Woods, 1984; Gandevia, 2001; St Clair Gibson, Lambert, & Noakes, 2001). Several underlying mechanisms have been proposed as being involved, and their contribution is likely to be very dependent on the mode, intensity and the duration of the exercise performed. It is likely that each of these theories may be, in part, responsible for a loss of performance. As a brief recap, the specific central and peripheral mechanisms that may be involved have been identified and defined as the following:

- Central fatigue is defined as a reduction in VA of the muscle during, or after exercise, as a result of mechanisms that originate proximal to the NMJ (i.e., within the CNS). The potential mechanisms highlighted in this review include:
  - Decreased excitatory input from the brain due to changes in neurotransmitters.
  - Decreased responsiveness and excitability of the motor neurons.
  - Increased inhibitory input due to peripheral feedback from type III and IV muscle afferents reducing motor drive.

- Peripheral fatigue is defined as mechanisms that occur at or distal to the NMJ. Peripheral fatigue is further sub-divided as LFF or HFF:
  - LFF refers to impairments in E-C coupling as a result of metabolite accumulation, energy substrate depletion and structural disruption of the individual muscle fibres.
  - The HFF theory suggests that the force-generating ability of a muscle is limited by its response to an electrical stimulus at the level of the sarcolemma or alpha motor neuron.

Several studies have investigated neuromuscular fatigue after real and simulated soccer matches (Table 8). In summary, these studies present evidence that the demands of soccer result in significant neuromuscular fatigue, originating from both central and peripheral mechanisms; persisting for up to 48 – 72 hours (Rampinini et al., 2011; Brownstein et al., 2017; Thomas et al., 2017; Goodall et al., 2017). Moreover, whilst central processes contribute significantly to the immediate declines in neuromuscular function, the typically slower recovery time course of peripheral indicators may explain the prolonged fatigue in the days post soccer activity.

2.6 ROLE OF THE ENDOCRINE SYSTEM IN ATHLETIC PERFORMANCE

The hormonal response to a single or a repeated exercise stimulus has drawn focus from researchers and performance scientists for several decades. Many previous studies have reported various hormonal responses during the immediate or prolonged post-exercise recovery period in a range of team sports (Elloumi et al., 2003; Kraemer et al., 2009; West et al., 2014b). Furthermore, studies have assessed changes in hormone concentrations during intensified training blocks or competition phases with the aim of identifying over-training risks and provide an objective marker of an athlete readiness (Hooper et al., 1995; Mackinnon et al., 1997; Coutts et al., 2007a; Moreira et al., 2016). In addition, acute changes in hormones have been linked to changes in neuromuscular performance (Bosco et al., 2000; Crewther et al., 2011a; Cook et al., 2013). Whilst several hormones have been studied to monitor acute and chronic responses to exercise, the steroid hormones testosterone (T) and cortisol © have drawn particular focus in previous literature. This is due to the nature of their functions in regulating anabolic and catabolic activity and their importance in the development of strength and power characteristics (Teo, McGuigan, & Newton, 2001). The T and C response to resistance training, endurance training, contact and combat sports has been well documented in recent years, yet the responses in the hours and days following soccer activity are not well understood.

2.6.1 Testosterone

T is one of the most potent naturally secreted androgenic-anabolic hormones (Florini, 1970). Whilst the majority of T is bound to sex hormone-binding globulin (~44 – 60%), the remainder is either loosely bound to albumin or other binding proteins, or in its unbound or free form (Dunn, Nisula, & Rodbard, 1981). However, only ~0.2 – 2% of total T is in its most biologically active free form (Loebel & Kraemer, 1998). Therefore, the biological activity of T is regulated by its interaction with various binding proteins (Jeyaraj, Grossman, & Petrusz, 2005). The signal for production and release of T is regulated by the hypothalamus and its interaction with the CNS (Figure 13). More specifically, specific neurons in the hypothalamus produce and secrete gonadotrophin-releasing hormone (GnRH), which stimulates the anterior pituitary gland to secrete luteinising hormone (LH) and follicle-stimulating hormone (FSH), which activates the Leydig cells of the testes to secrete T (Kim, 2007) (Figure 13). A lesser concentration of T (< ~5%) is produced in the adrenal glands and the ovaries (Vingren et al., 2010).

Some of the genomic functions of T in relation to human performance include development of the nervous system and motor neuron, red blood cell production, bone development and muscle hypertrophy (Hinson, Raven, & Chew, 2007; Zitzmann et al., 2001; Crewther et al., 2011b). In skeletal muscle, T stimulates protein synthesis (anabolic effect) through binding to intracellular androgen receptors (AR), which is then translocated to the nucleus, inducing transcription of specific genes (Inoue et al., 1994; Gobinet, Poujol, & Sultan, 2002). In addition to the anabolic effects, T has anti-catabolic effects that are thought to include inhibition of C signalling by hindering the glucocorticoid receptor (Mayer & Rosen, 1977). Correspondingly, excess glucocorticoids may interfere with T signalling and reduce the production of T in the Leydig cells (Hiraoka et al., 1987; Hardy et al., 2005). Generally, it is the anabolic effects of T that are of interest to those involved in sports performance, but the anti-catabolic effects might also be important because they aid in the protection of muscle protein which may accelerate recovery mechanisms (Vingren et al., 2010).

In addition to the longer-term genomic effects, T is thought to possess several non-genomic effects which may enhance neuromuscular performance. These changes appear rapidly (e.g., seconds, minutes, or hours) and possible mechanisms highlighted in previous literature include:

- Inducing an increased concentration of Ca^{2+} as a result of T binding to steroid receptors on the membrane of cells (Estrada et al., 2003; Hamdi & Mutungi, 2010; Ding & Stallone, 2001).
- Increasing the speed of transmitting and processing neural information to and from skeletal muscle (Bonifazi et al., 2004).
- Changes in cognitive function (e.g., aggression, decision making, and motivation) (Aleman et al., 2004; van Honk, Peper, & Schutter, 2005; Hermans et al., 2006; McCall & Singer, 2012).

Through the non-genomic effects outlined above, there is a growing body of evidence in support of the relationship between T and explosive performance (Viru & Viru, 2005; Cardinale & Stone, 2006; Crewther et al, 2009b; Crewther et al., 2013; Gaviglio et al., 2014). Concentrations of T have been shown to be related to training motivation in 15 elite male rugby union players (Cook, Crewther, & Kilduff, 2013). In this study, the authors reported that the voluntary selected workloads (% of change from prescribed workloads) in the back squat and bench press were significantly correlated to pre-exercise T concentrations over a 5-week progressive training block (Figure 11). A pair of studies by Cook and Crewther (2012a & 2012b) investigated the effects of video clips on T concentrations and subsequent performance in 12 elite rugby union players. In one study, they compared the effects of three interventions (15-min each) performed before a competitive game on coach rated key performance indicators (KPIs). Interventions were either: (a), watching a video clip of successful skill execution by the player with positive coach feedback; (b), watching a video clip of successful skill execution by an opposition player with cautionary coach feedback; or (c), the player was left alone to self-motivate. They reported that not only did the positive video clip (i.e., intervention [a]), promote significant elevations in T concentrations (+ 12%), the subsequent coach rated KPIs were also superior (Cook & Crewther, 2012b). In the other study, Cook and Crewther (2012a) assessed the effects of a shorter (~4-min each) video clip (i.e., sad, erotic, aggressive, training motivational, humorous or a neutral control clip) on T concentrations and subsequent 3RM performance in a back squat. They reported that not only did the aggressive, erotic, and training video clips stimulate higher concentrations of T than the control or sad clips, the players also performed significantly better in the 3RM test than their counterparts (Cook & Crewther, 2012a). Taken together, these studies suggest that there is a relationship between T concentrations, motivation, and neuromuscular performance.

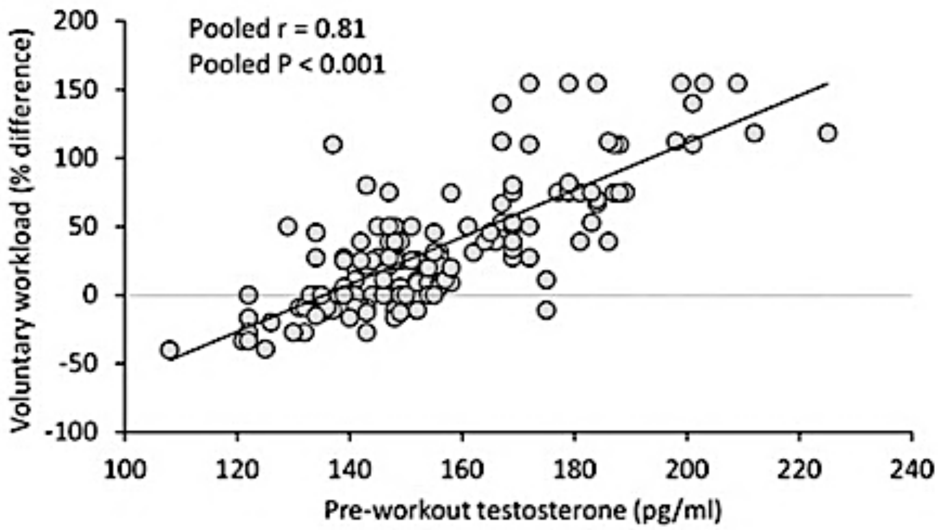

Figure 11. Scatterplot to show the pooled correlation between pre-workout T concentrations and voluntary workload in 15 elite male rugby union players (Reproduced from Cook, Crewther, & Kilduff, 2013).

Another factor to consider is that it seems that the training status or ability of the athlete may be related to the potential performance benefits of T. In strength-trained athletes, Crewther et al. (2012) examined the relationship between T and performance of back squats and sprints over time and the influence of baseline strength on this relationship. Here, 10 professional athletes from varied sports (e.g., athletics, rugby union) were split into 2 groups based on their 1RM squat strength. These groups were defined as 'good squatters' (1RM ≥2 x bodyweight, n = 5) and 'average squatters' (1RM <2 x bodyweight, n = 5). Each athlete was assessed for squat 1RM and 10 m sprint time on 10 separate occasions over 40 days, with T concentrations collected immediately before the testing. The pooled T correlations were strong and significant in the good squatters (r = 0.92 for squats, r = -0.87 for sprints), but not for the average squatters (r = 0.35 for squats, r = -0.18 for sprints) (Figure 12; Crewther et al., 2012). In support of this, it has been shown that strength-trained athletes can also produce greater post-workout changes in T than non-athletes (Tremblay, Copeland, & Van Helder, 2004; Ahtiainen et al., 2004). Furthermore, several studies have reported significant changes in T in response to exercise in well-trained athletes (Bosco et al., 2000; Jurimae & Jurimae, 2001; Ahtiainen et al., 2004; Crewther et al., 2011a), but lesser responses in non-athletes (Ahtiainen et al., 2004; West & Phillips, 2010). A likely explanation for this is that strength training is known to contribute to the development and recruitment of the larger type II muscle fibres (Folland & Williams, 2007). The development of these fibres may support the realisation of the steroid effects (Falduto, Czerwinski, & Hickson, 1990; Axell et al., 2006), and resistance training has been shown to regulate AR content in type II muscle fibres (Deschenes et al., 1994).

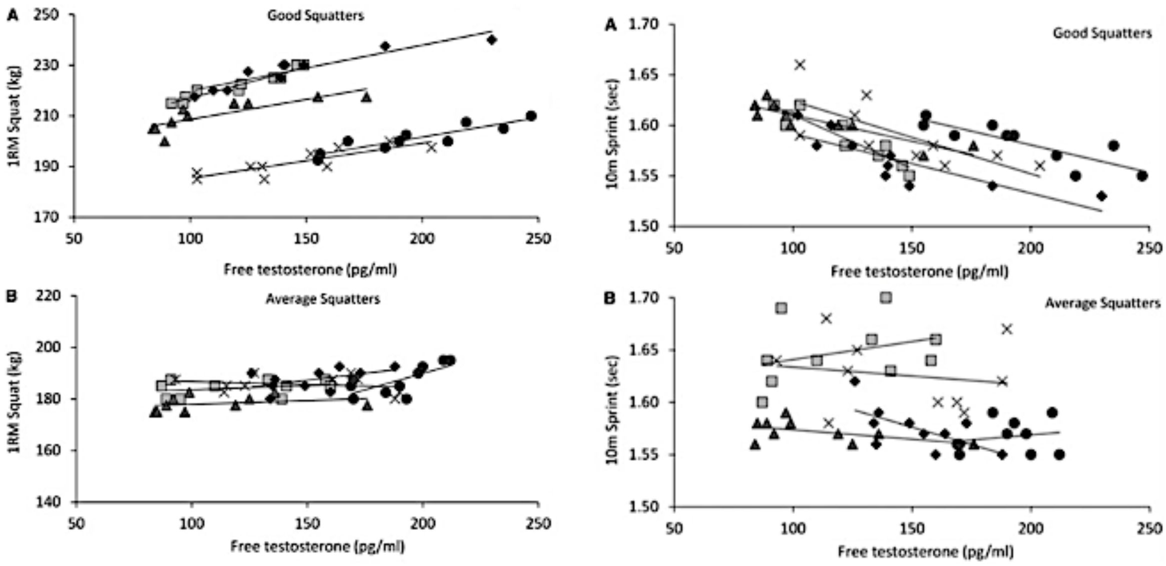

Figure 12. The linear regression lines between free testosterone and performance (1RM squat & 10-meter sprint times) in good and average squatting groups. Each symbol represents a different participant. Reproduced from Crewther et al., 2012.

Generally, T follows a normal circadian pattern of peaks in the morning (~08:00 h) followed by a progressive reduction (~30 – 40%) throughout the day (Dabbs, 1990; Cooke, McIntosh, & McIntosh, 1993). Considering the role of T in mediating cognitive function and athletic performance, offsetting this circadian decline may create an environment later in the day where performance is maintained. In 14 well-trained throwers, Ekstrand et al. (2013) demonstrated that a morning resistance training session (i.e., back squats to failure and power-clean exercises) resulted in improved afternoon throwing distance at 4 – 6 hours later. Similarly, Cook et al. (2014) assessed the effects of either morning sprints (5 x 40 m with 1-min recovery) or weight training (i.e., bench press and back squat routine up to 3RM) on T concentrations and afternoon physical performance (i.e., 40 m sprints, CMJ, 3RM bench press and back squats) in 18 semi-professional rugby union players. From morning to afternoon, T concentrations significantly declined under the control (-10.9 ± 2.4 pg·ml^{-1}) and sprints (-6.2 ± 7.1 pg·ml^{-1}) trials, but not the weights trial (-1.2 ± 5.5 pg·ml^{-1}). Furthermore, the declines in T were significantly greater in the control trial compared to the sprints and weights protocols. Players performed better in a CMJ, 40 m sprint, 3RM bench press, and 3RM squat after the weights compared with the control and sprints conditions. In addition, faster afternoon 40 m times were seen after the morning sprints when compared to the control trial (Cook et al., 2014). More recently, a study of 15 elite rugby players by Russell et al. (2016a) compared the effects of four different morning conditions. These were (a) passive rest, (b) weights (5 x 10 repetitions of bench press at 75% 1RM), (c) RSA (6 x 40 m maximal sprints, 20 s recovery), or (d), cycling (6 x 6 maximal sprints with 7.5% body mass load, 54 s recovery). The authors found that relative to control, afternoon T concentrations were greater and RSA performance was better after weights and running, but not the cycling protocol. Interestingly, afternoon JH increased after the morning cycling and running protocols, but not the weights. Furthermore, reaction times were unchanged after all protocols. Overall, these studies suggest that altering the circadian declines in T may enhance afternoon performance, which may have important implications for the sequencing of training and matchday preparation strategies.

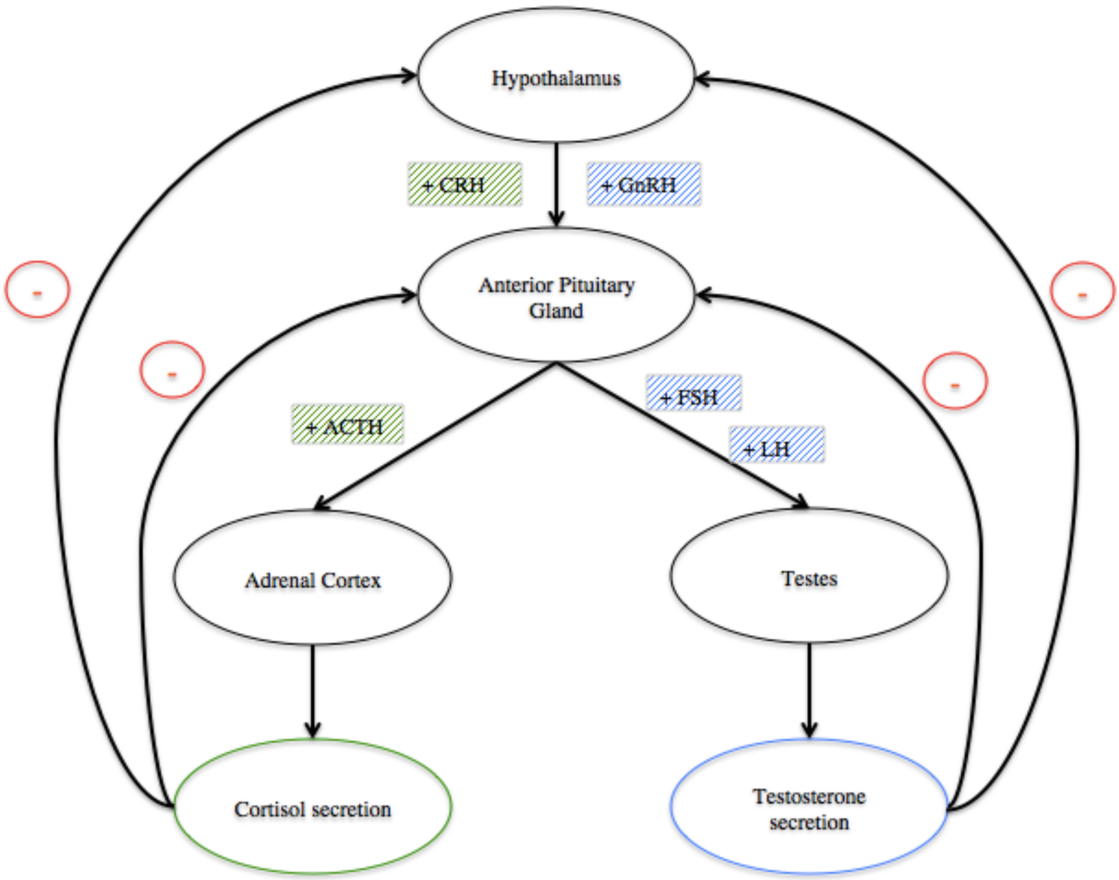

Figure 13. The hypothalamic-pituitary adrenal axis (green) and the hypothalamic-pituitary gonadal axis (blue), the process in which testosterone and cortisol are produced in men. Abbreviations: GnRH, gonadotrophin-releasing hormone; LH, luteinising hormone; ACTH, adrenocorticotrophic hormone; FSH, follicle-stimulating hormone; CRH, corticotropin-releasing hormone.

2.6.2 Cortisol

Another hormone that has drawn particular focus in sports and exercise science literature is C. A primary glucocorticoid, C is secreted from the adrenal cortex in response to the release of adrenocorticotrophic hormone (ACTH) from the anterior pituitary gland, which is regulated by the hypothalamus and its release of corticotropin-releasing hormone (CRH) (Figure 13; Kraemer & Ratamess, 2005; Tornhage, 2009). In circulation, C is mostly bound to plasma proteins, namely corticosteroid-binding globulin and albumin (Kraemer & Ratamess, 2005; Cizza & Rother, 2012). The free portion of circulating C constitutes ~5 – 10% of the total concentration and represents the biologically active fraction of C (Kraemer & Ratamess, 2005; Cizza & Rother, 2012). The primary metabolic functions of C are in gluconeogenesis, glycogenolysis, immune function, regulating lipolysis in adipose cells, and decreasing protein synthesis in skeletal muscle (Hooper et al., 1995; Erskin e et al., 2007). With regards to athletic performance, it has been suggested that the longer-term (i.e., weeks to months) catabolic functions of C have greater effects in type II muscle fibres (Solomon & Bouloux, 2006), which may have important implications in athletes who rely on strength, power, and speed for their sport.

Like T, C is thought to possess some more rapidly appearing non-genomic effects that may impact short-term changes in athletic performance. More specifically, changes in behaviour, cognitive function, energy metabolism and neuron activity (Crewther et al., 2011b). Many studies have reported that C concentrations are higher on a competition day before the start of warm-up in comparison to the same time of day on a neutral non-competition day (Passelergue & Lac, 1999; Gonzaalez-Bono et al., 1999; Suay et al., 1999; Salvador et al., 2003; Alix-Sy et al., 2008; Filaire et al., 2009). Moderate pre-event elevations in C have been demonstrated to positively correlate with weight lifted in a weightlifting competition (Passelergue, Robert, & Lac, 1995; Crewther, Heke, & Keogh, 2011), successful outcome in judo matches (Suay et al., 1999; Salvador et al., 2003; Papacosta, Nassis, & Gleeson, 2016), and 7-min rowing performance (Snegovskaya & Viru, 1993). However, extreme elevations in C may be undesirable for performance. Indeed, some studies have shown that marked elevations in C correlate negatively with outcomes in wrestling (Cintineo & Arent, 2019) and tennis matches (Booth et al., 1989; Filaire et al., 2009). It has been suggested that the anticipatory rise in C prior to competition is thought to reflect a psychophysiological mechanism influenced by cognitive anticipation and anxiety used by athletes as an arousal and coping mechanism to manage pre-competition stress. Thus, it is possible that some discrepancy in the literature may be related to genetics, the experience of the athlete and their ability to cope with competition anxiety, or via negative influences on T production and function. On the other hand, the ability of the opponent may influence the pre-competition changes in C. For example, if an athlete anticipates that they are going to be competing against a highly athletic and skilled opponent, a negative competition outcome may be inevitable despite the potentially positive non-genomic functions of moderate elevations in C.

Many previous studies have shown acute elevations in C following a bout of resistance exercise (e.g Hakkinen et al., 1988; Kraemer et al., 1993; Kraemer et al., 1999; Guezennec et al., 1986). Furthermore, it seems that exercises that provoke the greatest C response also elicit the greatest acute growth hormone and BLa response. Indeed, significant correlations between post-exercise concentrations in BLa and C have been reported (Kraemer et al., 1989; Ratamess et al., 2005). In addition, acute elevations in C have been correlated to 24-hour post-exercise markers of muscle damage (Kraemer et al., 1993). Metabolically demanding protocols high in total work (i.e., high volume, moderate – high-intensity with short rest periods), have stimulated the greatest acute BLa and C response, with a less pronounced change during strength and power training with longer rest periods (Kraemer et al., 1987; Hakkinen et al., 1988). Some strength training sessions have failed to elicit a significant C response whereas hypertrophy and endurance protocols performed by the same group of participants elicited more substantial elevations at 30-min post-exercise (Zafeiridis et al., 2003; Smilios et al., 2003). Whilst the exact time required for C to return to baseline is likely to be highly individual and dependent on the exercise protocol used, most studies report that C concentrations start to decline at 60-min post-exercise (Izquierdo et al., 2009; Kon et al., 2010; McCaulley et al., 2009). Lastly, similarly to T, under control conditions peak values of C concentration are generally seen in the morning (~1-hour post waking up), with a gradual reduction throughout the day (Dimitriou, Sharp, & Doherty, 2002). Therefore, if looking to monitor C over time, whilst concentrations may not be significantly elevated from baseline, they may be significantly altered from those expected for that time of day under control conditions.

2.6.3. Summary of testosterone and cortisol

The hormones T and C have been identified as possessing several genomic and non-genomic functions, that are likely to have potent acute and chronic influences on the neuromuscular system. Numerous studies have reported that an anabolic environment (i.e., an increase in T with a reduction or maintenance in C) may result in increased acute explosive performance and longer-term beneficial adaptations to exercise (Crewther et al., 2011b; Cook et al., 2014; Russell et al., 2016a). However, the responses of T and C to soccer activity are not well understood, and a greater understanding of how these hormones interact with neuromuscular performance, fatigue and recovery mechanisms in soccer may be beneficial and is warranted.

2.7 MONITORING THE TRAINING RESPONSE

Monitoring the athlete response to a physical stimulus is a predominant theme in sport and exercise science literature. Whilst section 2.4 has discussed how the external demands of soccer are established (e.g., GPS, accelerometers, video-based analysis), determining the athlete response is imperative for several reasons. Firstly, this can inform the coach on the readiness of the athlete to meet the demands of the next activity they wish for them to perform or justify periods of reduced training load or recovery. Secondly, monitoring discrete changes in performance at various times throughout a season can inform coaches on the adaptations to the previous training block, which can then direct further training strategies. Furthermore, the data can provide information regarding the magnitude and mechanisms of fatigue that may be present in response to various types of exercise, and how this may influence adaptations to training. In applied settings, monitoring strategies are very common in soccer (Akenhead and Nassis, 2016). There are numerous methods used for this in previous literature, such as physical performance tests (e.g., measures of neuromuscular function), athlete self-report questionnaires, measures of the autonomic nervous system (e.g., HR, HR variability), biochemical, immunological, and endocrine markers (Akenhead and Nassis, 2016; Thorpe et al., 2017). In applied settings, methods that are practical to administer and non-invasive to the athlete are preferred. This is not always the case in research, and whilst laboratory methods undoubtedly have benefits in understanding underlying mechanisms of fatigue, they are not always practical to implement in applied environments. This section will review some common strategies that have been used, both in prior literature and in applied settings to monitor the athlete response to training.

2.7.1 Neuromuscular function

Changes in the neuromuscular system (e.g., performance, fatigue, PAP) have been studied using a variety of methods, ranging from laboratory-based techniques (e.g., TMS, EMG, ITT) to field-based measures of performance (e.g., sprinting and jumping). When studying neuromuscular fatigue, laboratory-based measurements have traditionally been used in combination with an isometric MVC to identify the contribution of central and peripheral mechanisms outlined in section 2.5 (Taylor & Gandevia, 2008). Whilst these are useful for identifying the origin of fatigue, there are some limitations associated with these methods, particularly in applied environments (Cairns et al., 2005). An isometric MVC of a single muscle group does not always relate to neuromuscular function in a dynamic movement, which is more reflective of athletic performance (Bosco et al., 2000; Cairns et al., 2005). Indeed, several studies have found either weak or non-significant relationships between single-joint isometric strength and dynamic performance (Nakazawa et al., 1993; Murphy & Wilson, 1996; Wilson & Murphy, 1996; Ugarkovic et al., 2002; Requena et al., 2009). For example, when establishing the physical qualities of 21 semi-professional soccer players, Requena et al. (2009) reported weak or non-significant relationships between functional measures of performance (i.e., 15m sprint time, jumps) and isometric maximal force of the knee extensors and plantar flexors. This is likely a result of diverse motor unit recruitment and activation patterns between isometric and dynamic muscle contractions (Nakazawa et al., 1993; Requena et al., 2009). Accordingly, it has been suggested that there is a limit to how much can be drawn from such laboratory-based assessments regarding functional human movement (Cairns et al., 2005).

A dissociated recovery time course between isometric and dynamic contractions has also been reported after fatiguing exercise protocols (Byrne & Eston, 2002; Andersson et al., 2008; Beneka et al., 2013; Kennedy & Drake, 2018). In 17 elite male rugby union players, Kennedy and Drake (2018) observed a dissociated recovery time course between isometric squat strength and CMJ performance after a high-intensity back squat resistance training session. Whilst both variables were immediately impaired, isometric squat performance had recovered at 48 hours post, whilst CMJ variables were still significantly lower than baseline. Furthermore, there were no significant correlations between the pre to post percentage changes in the two measurements (Kennedy & Drake, 2018). Another study by Byrne and Eston (2002) compared the recovery time course of strength (i.e., knee extension isometric MVC) vs power (i.e., peak power attained in a Wingate test) after a very demanding protocol (i.e., 10 sets of 10 eccentric squat repetitions). The authors reported that whilst both measures declined after 1-hour, strength recovered in a linear pattern over the next 7 days, whereas, power declined further in the following 2 days before starting to recover (Byrne & Eston, 2002).

In soccer, some, but not all investigations have found differences between dynamic movements and low-velocity contractions. In 17 elite female soccer players, Andersson et al. (2008) reported that immediately after a match, isokinetic knee extension peak torque, 20 m sprint performance and CMJ height all declined immediately. After 5 hours, each marker had returned to near baseline, after which, sprint performance remained near baseline while CMJ height and peak torque experienced a secondary decline. From here, they were shown to recover at different rates, with peak torque recovering at 27 hours while CMJ height was still below baseline after 72 hours (Andersson et al., 2008). However, two of the studies reviewed in section 2.5.3 investigating the aetiology of neuromuscular fatigue after real (Brownstein et al., 2017) and simulated matches (Thomas et al., 2017) in semi-professional male players found that CMJ height presented a similar decline and recovery time course to other measurements of neuromuscular fatigue (i.e., isometric MVC of the knee extensors). Yet, broad jumps and sprint performance were less sensitive in assessing the neuromuscular response, which has been reported elsewhere (Gathercole et al., 2015).

Some of the studies outlined above raise questions around the relationship between both isometric and isokinetic measures of strength and more dynamic measures of the neuromuscular system, which are arguably more reflective of athletic performance (Cairns et al., 2005). Moreover, many isometric and isokinetic measures typically assess the movement around a single joint (e.g., knee extension), whereas jumping and sprinting performance is the product of the force and velocity expressed by multiple joints (Mitchell & Sale, 2011). As such, the value of isometric and isokinetic testing in applied environments as a marker of neuromuscular fatigue has been questioned (Cairns et al., 2005).

2.7.2 The use of jumps to assess neuromuscular function

Given the potential limitations associated with the laboratory, isometric and isokinetic measures outlined above, many researchers have investigated changes in movements that better replicate the sporting demands. Therefore, the use of dynamic and ballistic movements such as sprints and jumps are often used in previous research as both a performance indicator and a marker of fatigue (Andersson et al., 2008; Nedelec et al., 2012). However, in applied settings, the use of sprints as a fatigue marker is impractical, as both repeated and maximal sprints carry a risk of inducing further fatigue or risk of injury (Gathercole et al., 2015; Carling et al., 2018). Therefore, the assessment of vertical jump performance is a very common method used to determine neuromuscular function, both in research and applied environments (Cormack, Newton, & McGuigan, 2008; Akenhead & Nassis, 2016; Thorpe et al., 2017). These are safe, quick to perform on equipment that is usually portable, and therefore a practical to implement consistently, which facilitates the measurement of many subjects in a relatively short timeframe (Carling et al., 2018). Historically, the two most common jump variations in previous literature are either with a countermovement (i.e., CMJ) which involve recruitment of the SSC, or alternatively, without a countermovement (i.e., SJ) so that the eccentric component of the jump is removed and only the concentric phase is assessed (Nedelec et al., 2012; Van Hoore & Zolotarjova, 2017). Due to most athletic and team sport movements involving repetitive high-force SSC actions (e.g., sprinting, changing direction, jumping), it is suggested that the CMJ is the more appropriate jump type to monitor the response to this mode of exercise (Komi, 2000; Nicol, Avela, & Komi, 2006; Nedelec et al., 2012). Previous authors have suggested that exercises involving the SSC are sensitive to metabolic, mechanical, and neural elements of fatigue (Nicol, Avela, & Komi, 2006; Claudino et al., 2017). For these reasons, CMJ performance is well established as a primary marker of neuromuscular function (Jones et al., 2016a; Claudino et al., 2017).

The performance of a CMJ can be determined in several ways, with considerable variation across the literature in both the equipment used and the metrics derived from the jump. With regards to the equipment used, there are several tools available (e.g., contact mats, photoelectric cells, linear position transducers), however, the use of a force platform (FP) is considered the criterion measure (Glatthorn et al., 2011). Vertical jumps performed on a FP permits the calculation of several variables, with JH being the most popular in previous literature (Cormack, Newton, & McGuigan, 2008; Johnston et al., 2014; Jones et al., 2016a). Numerous researchers have reported excellent intra- and inter-day reliability for JH over a range of assessment methods, with CV values ranging from 1 – 6% (Cormack, Newton, & McGuigan, 2008; Moir, Garcia, & Dwyer, 2009; McMaster et al., 2014). Furthermore, JH has been shown to have significant relationships with linear acceleration and speed in rugby union (Cunningham et al., 2013), rugby league (Cronin & Hansen, 2005), AFL (Young, Cormack, & Crichton, 2011), and soccer players (Wisloff et al., 2004; Northeast et al., 2019). Furthermore, JH has been shown to discriminate between 'successful' and 'less-successful' athletes in several team sports, notably American football (McGee & Burkett, 2003), rugby league (Baker, 2001) and soccer (Arnason et al., 2004).

It should be acknowledged that some authors have questioned the sensitivity of JH as a marker of fatigue (Cormack, Newton, & McGuigan, 2008; Rowell et al., 2017). In soccer literature, whilst most studies do report JH to decrease in response to a match (e.g., Andersson et al., 2008; Ispirlidis et al., 2008; Magalhães et al., 2010), some have reported no change (Thorlund, Aagaard, & Madsen, 2009; Krustrup et al., 2010). Furthermore, some studies have reported that JH is not sensitive to daily fluctuations in training load across a microcycle in elite soccer

(Thorpe et al., 2015; Malone et al., 2015b). Previous authors have suggested this may be a result of a change in jump strategy, whereby proficient jumpers may alter their mechanics under fatigue to maximise the height of the jump (Cormack, Newton, & McGuigan, 2008). Other researchers have questioned the validity of JH as an indicator of lower limb maximal power output (Morin et al., 2019). Morin and colleagues (2019) suggested that individual body mass, the distance of push-off, optimal loading and force-velocity characteristics may confound the height of the jump and maximal power relationship (Morin et al., 2019). For these reasons, the efficacy of other CMJ derived variables (e.g., peak power output [PPO], mean power [MP], rate of force development [RFD], peak velocity [PV], peak force [PF], the ratio of flight time to contraction time [FT:CT], maximum rate of force development [mRFD]) has been explored (Gathercole et al., 2015). It is beyond the scope of the current review to discuss each of these metrics in detail, but the determination of PPO from a CMJ is a well-established marker of neuromuscular performance used extensively in previous literature (Hori et al., 2009; West et al., 2014a; West et al., 2014b; Owen et al., 2014; Johnston et al., 2017; Birdsey et al., 2019). Indeed, excellent intra- and inter-day reliability values (CV = 2.3 – 2.7%) for PPO have been reported previously (Hori et al., 2009; Gathercole et al., 2015; Birdsey et al., 2019), and it has been shown to be sensitive in detecting changes in neuromuscular function following soccer matches (Russell et al., 2016b).

2.7.3 Muscle damage and biochemical markers

Whilst direct measures of the neuromuscular system outlined above are undoubtedly important, one of the key explanations for a loss of performance is often exercise-induced muscle damage (EIMD). This is thought to be either mechanical, metabolic or a combination of both dependent on the mode, intensity, and the duration of the exercise performed (Tee, Bosch, & Lambert, 2007). As detailed in sections 2.2 and 2.3 of this review, many of the key game demands in soccer involve repeated eccentric muscle contractions, which are well established as having a high potential to induce muscle damage (Nedelec et al., 2012; Khaitin et al., 2021). Eccentric muscle contractions leave the muscle fibres in an unstable stretch and therefore more susceptible to mechanical disruption (Butterfield, 2010). This is characterised by microtrauma of the individual muscle fibres resulting in disruption at the level of the sarcomeres, a loss of Z-disk integrity and impaired E-C coupling (Clarkson, Nosaka, & Braun, 1992; Proske & Morgan, 2001). Whilst this mechanical model is the most popular theory, there is also evidence that metabolic stress may also result in EIMD (Tee, Bosch, & Lambert, 2007). For example, significant elevations in plasma and serum concentrations of intramuscular enzymes (e.g., CK) have been observed after long-distance cycling, which primarily involves concentric muscle contractions (Koller et al., 1998; Saunders, Kane, & Todd, 2004). The metabolic stress model proposes that the initial events of EIMD are caused by a complex cascade of events that result in metabolic deficiencies within the working muscle (e.g., ATP reduction, changes in Ca^{2+} buffering), or that these deficiencies increase the vulnerability of the muscle fibre to mechanical stress (Armstrong, Warren, & Warren, 1991; Tee, Bosch, & Lambert, 2007). There is also evidence to suggest that EIMD may disturb the time course of other key recovery mechanisms. For example, compared to control groups, reduced glycogen concentrations of eccentrically damaged muscles have been observed, which may predominantly affect type II muscle fibres (Costill et al., 1990; Ivy, 2004). This has significant implications for athletes who rely on strength, power, and speed for performance.

As a result of the influence of muscle damage on neuromuscular performance outlined above, several measurements are often used as indirect markers of EIMD. These include self-reported muscle soreness, range of motion, and a range of biomarkers (e.g., CK, myoglobin, lactate dehydrogenase, alanine aminotransferase, aspartate aminotransferase) (Tee, Bosch, & Lambert, 2007; Koch, Pereira, & Machado, 2014; Silva et al., 2018). It is beyond the scope of this review to discuss each of these in detail, however, the most common biochemical marker of muscle damage in previous literature is CK (Silva et al., 2018). Within healthy muscle tissue, CK is predominantly located within the sarcolemma and mitochondrial inter-membrane space and is responsible for catalysing the reaction of phosphate from PCr to adenosine diphosphate (ADP), forming ATP and creatine (Clark, 1997; Brancaccio, Maffulli, & Limongelli, 2007). Therefore, CK is considered the primary enzyme associated with anaerobic metabolism (Brancaccio, Maffulli, & Limongelli, 2007). It is thought that due to its large molecular mass, CK cannot habitually diffuse directly into the capillaries, yet when muscle cell structure is damaged, CK leaks into the interstitial fluid and the lymphatic system before being emptied into the circulation (McLellan, 2010). Transport of fluid in the lymphatic system is relatively slow in comparison to the vascular system, which may explain the often-reported delay in peak concentrations of CK (~ 24 – 48 hours) post-exercise (Sayers et al., 2000).

Elevations in CK have been reported after many team-sport activities, such as rugby union matches (Gill, Beaven, & Cook, 2006), rugby league matches (e.g., McLellan, Lovell, & Gass, 2010), American football games (e.g., Kraemer et al., 2009), soccer matches (e.g., Andersson et al., 2008), as well as repeated sport-specific sprinting protocols (e.g., Howatson & Milak, 2009). With regards to soccer, typical elevations in CK concentration immediately post-match are between ~75 – 250% of baseline markers, with a peak (~125 – 350%) occurring between 24 – 48 hours of recovery, before returning to near baseline levels generally after 72 – 96 hours, depending on the magnitude of the peak (Silva et al., 2018). It is worth noting that there has been debate in the literature around the reliability of CK as a recovery marker as there may be a high individual variation in both baseline concentrations and in response to exercise (Thompson et al., 1999; Warren et al., 1999; Urhausen & Kindermann, 2002). Despite this, it seems that changes in CK are a useful way to determine the magnitude of muscle damage post soccer-specific exercise. However, the magnitude of the CK response, its pattern of recovery, and the interaction between CK and other markers of recovery in response to many soccer-specific training exercises have not been studied.

2.7.4 Athlete self-report measures

Surveys on monitoring in elite sport demonstrate that athlete self-report measures are a very common method used for assessing the overall well-being of athletes (Taylor et al., 2012; Akenhead & Nassis, 2016). Often their use complements other measures, such as the biomarkers and tests of neuromuscular performance outlined in the previous sections. Many questionnaires have been proposed in previous literature (e.g., POMS, the Recovery-Stress Questionnaire, the Daily Analyses of Life Demands, the Multicomponent Training Distress Scale, the Total Quality Recovery Scale, and the Recovery Cue) (Shearer et al., 2017; Thorpe et al., 2017). However, many of these are often extensive and time-consuming to complete, which may limit their everyday use in a squad of athletes. Therefore, many teams implement customised questionnaires that are briefer and can be administered on a day-to-day basis, which likely increases athlete compliance (Taylor et al., 2012). Prior research in this area has shown that athlete self-report questionnaires are sensitive to changes in training load in both AFL and soccer (Gastin, Meyer, & Robinson, 2013; Buchheit et al., 2013; Thorpe et al., 2015; Gallo et al., 2017). One questionnaire that has been shown to be sensitive is the Brief Assessment of Mood (BAM+) questionnaire (Shearer et al., 2017). For example, 11 elite u-21 EPL soccer players were monitored across five matches whilst wearing 10 Hz GPS devices. In this study, CK and PPO were collected in conjunction with BAM+ at baseline, 24 and 48 hours post-matches. The authors concluded that the BAM+ was an effective tool for monitoring longitudinal recovery cycles in elite-level soccer players (Shearer et al., 2017). Furthermore, significant relationships were found between match external load parameters (i.e., total distance and HSR covered per minute and the number of sprints) and the changes in BAM+ scores from baseline to 24 and 48 hours post-match (Shearer et al., 2017). Similar conclusions were reported after an elite rugby match (Shearer et al., 2015).

2.7.5 Monitoring the training response summary

This section began with emphasising the rationale for monitoring the athlete response to exercise and detailed the benefits this may have for practitioners. Simply, not all athletes will respond to the same 'dose' of exercise in the same way, therefore, identifying this dose-response relationship is needed. Examples of contextual factors that may influence this are the athlete training history, age, genetics, and lifestyle factors (e.g., sleep, nutrition & hydration). Furthermore, as the movement patterns in soccer are inherently random and uncontrolled, there is likely to be variations in physical load during training and competition, which is very likely to result in varied responses. Indeed, monitoring has long been a primary focus in soccer literature, with a specific focus on the physiological responses to competition demands (Nedelec et al., 2012; Silva et al., 2018). Arguably, the responses to each activity that a player performs in a training program are also very important, considering the influence this may have on the design of training programs. More specifically, ensuring the training is organised in an appropriate way to target the adaptations required whilst also minimising fatigue leading into a competition, thus optimising performance.

Section 2.7.1 has highlighted some issues with using laboratory, isometric, and isokinetic methods to determine the neuromuscular response in applied environments. Whilst these measures certainly have their benefits in understanding the origin of fatigue (i.e., central and peripheral mechanisms), or in assessing strength imbalances, their application in applied environments may be limited. Instead, more dynamic measures that recruit the use of the SSC and are easy and safe to implement may be beneficial. Given this, section 2.7.2 has highlighted that monitoring CMJ performance is an accepted and well-established marker of neuromuscular function (Owen et al., 2014; Johnston et al., 2015a; Thomas et al., 2017). Section 2.7.3 has discussed the importance of monitoring indirect markers of EIMD since it is a key factor that influences fatigue. This section focused in on a very popular biochemical marker (i.e., CK) used to determine the magnitude of EIMD and its previously reported responses to soccer matches. Yet, the magnitude of the changes in CK and its time course of recovery in response to soccer training sessions are largely unknown. Finally, athlete self-report measures are very popular, non-invasive, and practical markers and seem to be sensitive to training and match external loads. The BAM+ has been identified as a useful and sensitive tool to detect the fatigue response to soccer matches (Shearer et al., 2017), however, it is advised that perceptual measures of recovery are used in conjunction with objective markers to ascertain the varied and multi-faceted nature of fatigue (Brownstein et al., 2017)

2.8 RESPONSES TO SOCCER, RESISTANCE AND CONCURRENT TRAINING

The neuromuscular, biochemical, hormonal, and perceptual responses to matches or competition performances are well documented from numerous sports. For example, these have been characterised in netball (Birdsey et al., 2019), rugby union (e.g., Duffield et al, 2012; West et al., 2014b), marathon running (Petersen et al., 2007), soccer (e.g., Nedelec et al., 2012), rugby league matches (e.g., McLellan, 2010), AFL competition (e.g., Cormack, Newton, & McGuigan, 2008), amongst many others. In addition, the chronic adaptations to SSG and resistance training are well established and described in sections 2.3.2 and 2.3.3. Instead, this section will focus on the acute responses to soccer training (section 2.8.1) and resistance training (section 2.8.2). Finally, sections 2.8.3 and 2.8.4 will review the literature on concurrent training, and the influence that the manipulation of programming variables may have on the interactions between different types of training modalities.

2.8.1 Acute responses to soccer training

There are a limited number of published studies on the acute neuromuscular, biochemical, or endocrine responses to soccer training. Chmura et al. (2019) examined T and C concentrations in response to a 1 vs 1 SSG with variable durations but constant work-to-rest ratios (i.e., 1:4). In this study, 18 young male soccer players were split into two groups. Group (a) completed a 1 vs 1 SSG in 6 x 30 s bouts with 2-min rest, and group (b) completed 6 x 45 s bouts with a 3-min rest period. Capillary blood samples were drawn at baseline, immediately after the last SSG repetition, and at 15 and 30-min intervals after the exercise protocols and assessed for T and C concentrations. The key finding from this study was that SSG protocol (a) provoked significantly elevated C at 15 (+32%) and 30-min post (+7%), whereas protocol (b) did not. The authors concluded that longer rest intervals (i.e., 6 x 45s with a 3-min rest period) resulted in lower catabolic responses in this cohort, concluding that this method of training would be beneficial in maintaining an anabolic environment and reduce the risk of overtraining. However, no markers of training load (e.g., GPS data, HR, RPE, BLa) or neuromuscular function were reported in this study. To the author's knowledge, this is the only study to assess the hormonal responses to SSG training. However, as the game format was limited to 1 vs 1, hormonal markers were only reported up to 30-min post-exercise, and no other monitoring markers were reported, there is clearly scope for future research in this area.

In 14 well trained female soccer players, Sjökvist et al. (2011) quantified the recovery time course after a training session consisting of high-intensity soccer drills. Here, the training sessions consisted of 4 sets of 4-min SSGs (4 vs 4) in combination with 4 sets of 4-min interval running over a soccer-specific course (described in Hoff et al., 2002), and each high-intensity drill was separated by 3-min of active recovery. Markers of neuromuscular performance (i.e., CMJ height, 5 horizontal bound jumps for distance, 20m sprint time) were taken at baseline and after 24, 48, and 72 hours of rest. The total training session resulted in RPEs of 7.0 – 8.6 AU (classified as 'very hard' on the Borg CR-10 scale used) and spent ~25-min between 80 – 100% of HR_{max}. Following training, there was a significant decline in CMJ height at 24 hours post, which returned to baseline after 48 hours, but no significant changes in 20 m sprint time or 5 horizontal bound jumps for distance at any time point. This study suggests that whilst high-intensity soccer training produces a potent conditioning stimulus, as evidenced by the RPE scores and the HR responses, this type of training may compromise training performance on the following day, but there is a lesser chance of under-recovery after 48 hours of recovery. Furthermore, this study suggests that CMJ performance may be a more sensitive recovery indicator than the other variables assessed.

A recent study by Ade et al. (2021) compared the acute neuromuscular responses from a novel speed endurance production (SP) training session vs a speed endurance maintenance (SM) training session in 20 elite male soccer players. The SP protocol consisted of 8 bouts of 30 s of maximal running interspersed by 150 s of recovery (1:5 work to rest ratio). The SM protocol included the same number of sets and repetitions but with the recovery reduced to 60 s (1:2 work to rest ratio). Unsurprisingly, the HSR (19.8 – 25.2 $km \cdot h^{-1}$) and sprinting distances (>25.2 $km \cdot h^{-1}$) were significantly greater in the SP in comparison to the SM protocol (HSR, +49%, sprinting +218%), likely due to the longer rest periods in the SEP allowing metabolic recovery and thus a higher running intensity. However, the HR responses were higher in the SEM protocol (SP, 75.1 – 79.9% mean HR_{max}; SM, 84.2 – 86.1% mean HR_{max}). Furthermore, the SP protocol resulted in more pronounced reductions in CMJ height immediately post-training (~2% difference between protocols), however, at 24 hours post, the SM protocol impaired CMJ height to a greater extent (~4% difference between protocols). In addition, horizontal jump performance was reduced immediately post both SP and SM (~3 – 5%), and by 24 hours post, SM was further impaired in comparison to SP (~4% difference between protocols). These results demonstrate that there may be a different neuromuscular response from soccer-specific exercises with varied rest periods. This is likely linked to the heightened metabolic (i.e., HR) response after the SEM protocol vs the increased external (i.e., HSR and sprinting) demands after the SEP protocol.

Together, these studies give some insight into possible acute neuromuscular and hormonal responses induced by high-intensity soccer training. Evidently, the quantity of literature in this area is limited. To date, only Chmura et al. (2019) have studied the hormonal responses to isolated SSG training, yet this only assessed a 1 vs 1 format up to 30-min post-exercise and reported no markers of training load or the neuromuscular response. A comprehensive battery of measurements has not been collected post SSG training, and further research in this area is warranted to improve our understanding of the responses to soccer training.

2.8.2 Acute responses to resistance training

As discussed in section 2.3.3, strength is a fundamental physical quality that underpins performance in soccer (Cormie, McGuigan, & Newton, 2011b; Turner & Stewart, 2014). Numerous studies have investigated the acute responses to various forms of resistance training sessions. However, the participant training history, exercise choice, volume and intensity of these sessions vary greatly, which should be considered when drawing inferences from the literature. For example, Beaven et al. (2008) classified 4 sets of 10 repetitions at 70% of 1RM as hypertrophy, whereas Linnamo et al. (2000) used a very similar protocol of 5 sets of 10 repetitions at 70 – 75% of 1RM and termed it 'explosive heavy resistance training'. While manipulation of resistance training variables can produce various responses and target different adaptations (e.g., hypertrophy, strength, power), and these are all linked, this review will focus on training aimed at the development of strength. As there is a discrepancy across the literature on the definition of strength training, this review will follow the guidelines on strength development recommended by previous authors (Kraemer, Duncan, & Volek, 1998; Beaven, Cook, & Gill, 2008; Johnston et al., 2016). This is characterised as resistance training that utilises ≤6 repetitions per set, at an intensity of ≥80% 1RM, with ≥3-min of recovery between repetitions.

A comprehensive study by McCaulley et al. (2009) monitored the neuromuscular and hormonal responses to resistance training sessions aimed at three distinct adaptations (i.e., strength, hypertrophy, and power). Each training session was designed to control for total work done, but with varied intensity, set and repetition schemes. Using a randomized cross-over design, 10 well trained male subjects performed strength training (11 x 3 repetitions at 90% of 1RM with 5-min rest), hypertrophy training (4 x 10 repetitions at 75% of 1RM with 90 s rest), or power training (8 x 6 repetitions at BW with 3-min rest), with a rest day as a control trial. The back squat was used for the strength and hypertrophy training, and the jump squat for the power training. Neuromuscular responses were evaluated using an isometric squat performed on a FP, whereby RFD at 200 ms and PF were the key variables assessed. Additionally, EMG activity of the vastus medialis (VM) was monitored. Blood samples were also drawn and evaluated for lactate, T, C, and sex hormone-binding globulin (SHBG) concentrations. Time points of data collection were pre, immediately post, 60-min post, 24 hours, and 48 hours post-training. With regards to neuromuscular function, PF and RFD were reduced after the strength and hypertrophy, but not the power training session (Figure 14). Furthermore, the strength session resulted in significant decreases in VM muscle activity, whereas the hypertrophy session resulted in a slight increase, with no changes reported after the power session. The recovery rate of RFD was distinctly slower after strength training in comparison to hypertrophy training, which may indicate strength training induces a greater disturbance of CNS function than other forms of training. The results from this study suggest that strength and hypertrophy training produce similar disturbances in neuromuscular performance, yet the mechanisms may be different. It seems that that intensity, number of repetitions per set, and time of recovery between sets all have a greater influence than total work done on neuromuscular performance (Figure 14).

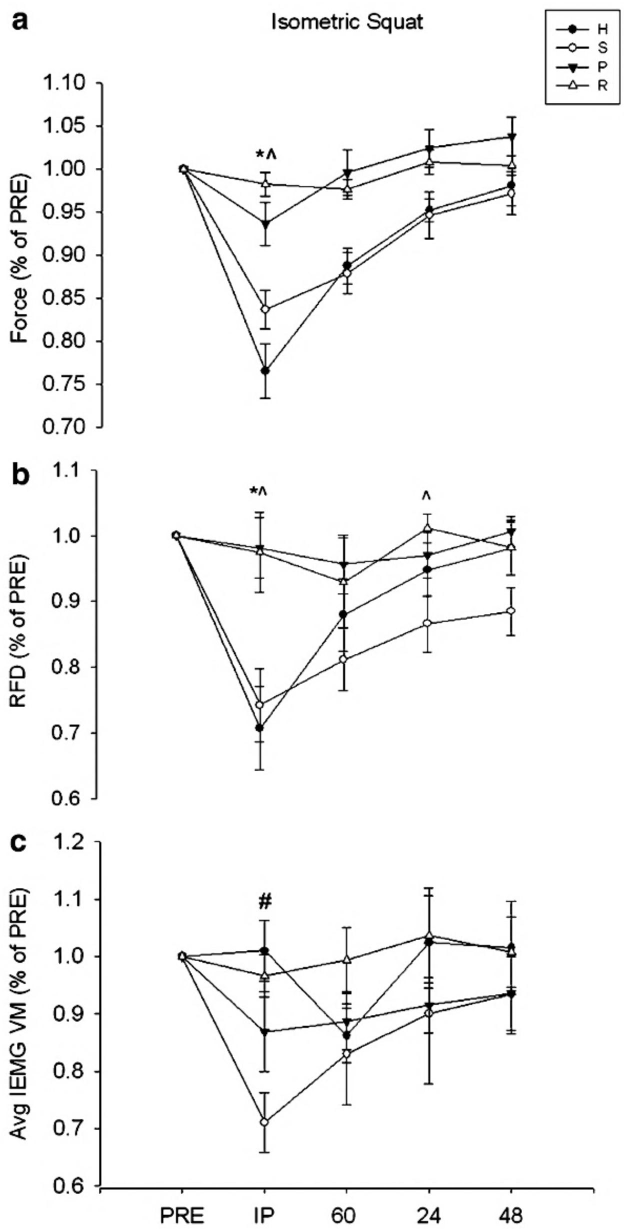

Figure 14 (A – C). Comparison of the mean: (**a**) percent of baseline PF values; (**b**) percent of baseline RFD values; and (**c**) percent of baseline average EMG muscle activity from the vastus medialis at immediately post exercise (IP), 60 minutes (60P), 24-h (24P), 48-h (48P) between the hypertrophy (H), strength (S), power (P), and rest (R) conditions during an isometric squat test. *H protocol significantly ($p < 0.05$) decreased in comparison to R condition. ^ S protocol significantly ($p < 0.05$) decreased in comparison to R condition. # H protocol significantly ($p < 0.05$) increased in comparison to S protocol. Reproduced from McCaulley et al., (2009).

As previously mentioned, the hormonal and BLa responses were also assessed in response to the three training sessions in the above study (McCaulley et al., 2009). There was a unique response observed in T, C, SHBG and BLa for each resistance training protocol (Figure 15). In comparison to the rest condition, the hypertrophy protocol resulted in a significant change in T, C, and SHBG from pre to immediately post-training, whereas no significant changes were evident after strength or power training. The BLa response following the hypertrophy session was significantly greater than all other protocols. This follows the consensus in the literature that hypertrophy type resistance training sessions induce greater BLa accumulation and increased hormone responses in comparison to other protocols (Kraemer & Ratamess, 2005; Crewther et al., 2006). With regards to the strength training protocol, there seemed to be an immediate increase in T (+19.6%) along with a decrease in C (-18.2%) in comparison to baseline, although this was not statistically significant (Figure 15). This suggests that strength training is likely to produce an anabolic response, but to a lesser extent than hypertrophy training. In summary, this study proposes that the total work completed in a resistance training session is not a critical variable in eliciting the acute hormonal response. Rather, much like the above-mentioned changes in neuromuscular performance, the intensity and rest periods between repetitions influence the hormonal responses more prominently.

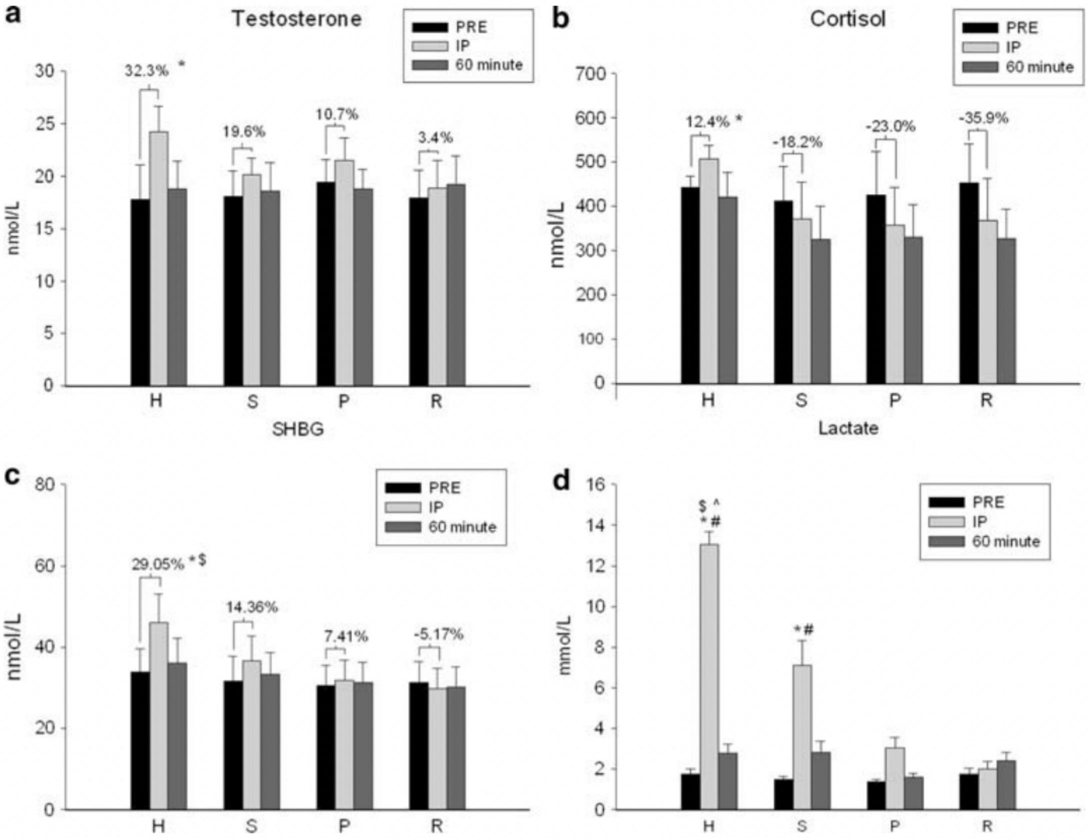

Figure 15 (A – D). Comparison of (**A**) total serum T concentration; (**B**) total serum C concentration; (**C**) total serum SHBG concentration; and (**D**) lactate concentration at rest (PRE–black bars), immediately post exercise (IP–light grey bars), and at 60-minutes following completion of exercise (60P–dark grey bars) for each resistance exercise protocol (hypertrophy [H], strength [S], power [P] and rest [R]). The numbers represent the percent change from pre to IP. #Significant ($p < 0.001$) difference from pre value; *significant ($p < 0.05$) difference from R protocol; $significant ($p < 0.05$) difference from P protocol; ^significant ($p < 0.05$) difference from S protocol. Reproduced from McCaulley et al., (2009).

Another study in this area by Beaven, Gill, and Cook (2008) investigated the acute salivary T and C concentrations in response to four different resistance training protocols in 23 elite male rugby players. Participants completed each training protocol in random order with at least two days of recovery given between trials. Salivary T and C samples were obtained at baseline, immediately post-training and at 30-min post-training. The training session consisted of four compound exercises with the aim of recruiting considerable muscle mass (i.e., bench press, leg press, seated row, and back squat). It has been previously shown that the recruitment of greater total muscle fibres results in a greater hormone-tissue interaction (Kraemer & Ratamess, 2005).

The four training protocols Beaven and colleagues (2008) investigated were as follows:

- (a) 4 sets of 10 repetitions at 70% 1RM with 2-min rest between sets.
- (b) 3 sets of 5 repetitions at 85% 1RM with 3-min rest between sets.
- (c) 5 sets of 15 repetitions at 55% 1RM with 1-min rest between sets.
- (d) 3 sets of 5 repetitions at 40% 1RM with 3-min rest between sets.

Results revealed that T concentrations did not significantly change as a result of any of the resistance training protocols, with no significant differences between trials. However, C declined significantly after all training sessions except for protocol (c). Individual athletes differed in their T response to each of the protocols, which was masked when examining the pooled group data. The findings left the authors to conclude that resistance training induced significant individual, protocol-dependent hormonal changes lasting up to 30-min after exercise. Essentially, it is highly likely that individual athletes respond differently to various resistance training protocols. Another factor to consider is that many rugby players may enjoy resistance training as a psychological break from the demands of field-based contact training (Beaven, Gill, & Cook, 2008). This could potentially affect the hormonal responses in a distinctive way to other athletic populations such as soccer players, who may react to the training stresses differently.

The studies outlined above support our understanding of the neuromuscular and hormonal response to various modes of resistance training. Yet, this data is specific to the population in which the studies were conducted, and the training protocols used. Notably, there is a limited quantity of research that has recruited high-level soccer players as participants in this area. Considering soccer players often complete two high-intensity sessions daily (e.g., one on-field and one resistance training session) (Cross et al., 2019), further investigation into the interaction between soccer training and strength training may be beneficial. Therefore, the following section will discuss previous research on concurrent training programs.

2.8.3 Concurrent training

A recurring theme in the preceding sections of this review is that soccer players should maintain and develop multiple physical qualities aligned to successful performance. There is a growing body of research indicating that the acute declines in neuromuscular performance induced by resistance training may impair endurance training performance, particularly during periods of resistance training-induced muscle damage (Wilson et al., 2012; Doma et al., 2019). Likewise, many studies report strength and power adaptations are attenuated when endurance training is also performed in comparison to resistance only training programs (Wilson et al., 2012; Fyfe et al., 2016; Lee et al., 2020). A survey completed by 43 rugby team staff conducted by Jones et al. (2016a) revealed that 72% of teams completed high-intensity rugby and resistance training on the same day. Similarly, a survey of 18 soccer teams conducted by Cross et al. (2019) reported that 78% of resistance training sessions were programmed on the same day as field training. This is problematic as the adaptations induced by resistance and endurance exercise are vastly different and, in many cases, conflicting (Leveritt et al., 1999; Hawley, 2009). Due to the often-limited training time between fixtures in soccer (e.g., 3 – 7 days), this is unavoidable, and concurrent training practises must be implemented in an attempt to develop or maintain the multiple physical qualities required.

There is an abundance of literature in the area of concurrent training, yet the majority of this is focused on conventional endurance training (e.g., steady-state or interval running or cycling) in combination with various modes of resistance training (Wilson et al., 2012; Doma et al., 2019; Lee et al., 2020). It is well known that adaptations in skeletal muscle tissue are specific to the signals imposed by variations in the modality of exercise performed. For example, endurance athletes demonstrate increased mitochondrial density, with no change or a small increase in the hypertrophy of type I fibres, with maintenance or a decrease in type II fibre size (Edström & Ekblom, 1972; MacLean, Graham, & Saltin, 1994). In contrast, elite powerlifters and Olympic weightlifters who consistently train at high percentages of their 1RM demonstrate superior hypertrophy of type II fibres and have a lower mitochondrial density in comparison to the general population (MacDougall et al., 1979; Fry, 2004). At a molecular level, resistance training increases net protein synthesis in the myofibrillar subfraction, whereas endurance exercise increases net protein synthesis in the mitochondrial subfraction (Wilson et al., 2012). There are several physiological mechanisms proposed in previous literature to explain the potential causes of the interference effect from concurrent strength and endurance training. These factors include:

- Conflicting hormonal profiles (e.g., anabolic response from resistance training vs catabolic response from endurance training) (Bell et al., 2000).
- Different molecular signalling pathways, such as activation of AMP-activated protein kinase (AMPK) from endurance training impairing muscle adaptation by inhibiting mechanistic target of rapamycin (mTOR) (Atherton et al., 2005; Spiering et al., 2008b; Hawley, 2009).
- Impaired neuromuscular function and muscle soreness, resulting in reduced performance of a second training session (Doma, Deakin, & Bentley, 2017).
- Reduced movement efficiency as a result of changes in the kinematics of exercise and increased energy expenditure (Doma, Deakin, & Bentley, 2017).
- Reduced muscle glycogen stores impairing the performance of multiple daily training sessions (Doma, Deakin, & Bentley, 2017).

Considering the factors bullet-pointed above, designing effective concurrent training programs for team-sport athletes that rely on both aerobic capacity and strength for optimal performance appears to be a challenging task. Those responsible for the design of concurrent training programs should consider the variables that may mitigate the interference effect. It has been shown that the training order and between-session recovery time may influence the performance of training, the recovery dynamics, and the severity of interference in chronic adaptations (Wilson et al., 2012; Doma et al., 2019). Therefore, the following section of this review discusses the influence that manipulating those variables may have on mitigating the interference effect.

2.8.4 Training order and between-session recovery time

The surveys published by Cross et al. (2019) and Jones et al. (2016a) mentioned above provide some insight into the current practises in elite team sport. In soccer, 92% of teams reported that field-based training was performed before resistance training (Cross et al., 2019). Unfortunately, the recovery time between sessions was not a question asked in this survey. In rugby union, 77% of respondents considered the potential of muted strength development when programming concurrent training, and 63% believed that resistance before aerobic training was favourable for strength development than vice versa (Jones et al., 2016a). However, when ranked by order of importance, 56% of respondents considered the sequence of strength and endurance training as being of 'high importance', yet only 31% perceived the time between strength and endurance training as being of 'high importance' (Jones et al., 2016a). This is thought-provoking considering the growing body of literature that suggests that training order and between-session recovery time may influence the responses to concurrent training.

Robineau and colleagues (2016) compared the adaptations after a 7-week training block in 58 amateur rugby players that undertook resistance training followed by endurance training (i.e., interval running). Conditions were either that the training sessions were performed (a) back-to-back (i.e., no between-session recovery time), (b) with 6 hours of recovery, or (c) on alternate days with 24 hours of recovery. This study revealed that gains in 1RM for bench press and half squat were lower in condition (a) compared with conditions (b) and (c). In addition, the magnitude of the increase in VO_{2max} was greater in group (c), where 24 hours of between-session recovery was given. This study suggests that there may be interference in both strength and aerobic adaptations when resistance and endurance training is performed on the same day, and this is most prominent when there is insufficient recovery time between sessions (Robineau et al., 2016).

An early study in this area by Sale et al. (1990) investigated the differences between same-day vs alternate-day resistance and cycling interval training. The study was conducted over 20 weeks with 15 recreationally trained athletes. The alternate-day training group significantly improved leg press 1RM (+25%) compared to the same-day training group (+13%). Interestingly, markers of hypertrophy and muscular endurance increased to a similar extent in both groups, with the cross-sectional area of the knee extensors, knee flexors, and the maximal number of leg press repetitions performed at 80% 1RM not significantly different between groups (Sale et al., 1990). This suggests that the interference effect of concurrent training may affect maximal strength to a greater extent than hypertrophy. Furthermore, at the end of the study, cycling VO_{2max} was similar between the two groups (+6 – 7%), which contradicts the findings of Robineau et al. (2016). As the two studies varied in the modes of endurance training (running vs cycling), this may explain the differences between findings. This is supported by a review by Wilson and colleagues (2012), who found that strength training concurrently with running, but not cycling, resulted in greater decrements in both hypertrophy and strength. A likely explanation for this is a difference in contraction types. Running has a high eccentric component, whereas cycling is predominantly concentric. These differences in contraction types (eccentric vs concentric) may create greater muscle damage after running in comparison to cycling. For example, it has been shown that long-distance running results in a greater magnitude of muscle damage in comparison to long-distance cycling (Koller et al., 1998). Considering that soccer is a running based sport involving many eccentric muscle contractions, the interference effect may be augmented.

In 23 recreationally active men, Fyfe et al. (2016) demonstrated that compared to 8 weeks of resistance only training, cycling training performed 10-min before resistance training reduced improvements in lower-body strength, lean mass, as well as CMJ performance. However, as only 10-min of recovery was given between sessions and the order of training was not manipulated, this may have influenced the results. Concerning this, a recent study by Lee et al. (2020) investigated the effects of manipulating the training session order of cycling and resistance training, but with 3 hours of recovery given between sessions, as opposed to the 10-min given by Fyfe et al. (2016). In this study, 3 training groups were compared after a 9-week training intervention. Group (a) performed resistance only training (n = 9), group (b) performed cycling interval training 3 hours before resistance training (n = 10), and group (c) performed resistance training 3 hours before the cycling interval training (n = 10). After the 9-week training period, all training groups increased leg press 1-RM (~24 – 28%) and total lean mass (~3 – 4%), with no significant differences between groups. Furthermore, both concurrent groups (groups b & c) elicited similar *small-to-moderate* improvements in VO_{2max}, (+8 – 9%). Interestingly, in this study, the only variable that seemed to be attenuated by the concurrent training groups was CMJ performance, with peak power reduced by ~7 – 9% in the concurrent training groups compared to the resistance only group. This agrees with the findings of numerous other studies that suggest concurrent training may impair muscular power to a greater extent than aerobic capacity (Chtara et al., 2008; Leveritt et al., 1999; Wilson et al., 2012; Fyfe et al., 2016).

The studies discussed above recruited amateur or recreationally active participants, therefore cannot necessarily be generalised to highly trained or elite athletes who are likely to have a significantly greater training history or differences in gene expression (Heffernan et al., 2015). In addition, the responses may be sport dependent due to differing athlete anthropometrics, training and competition demands. There are a limited number of studies that have investigated the influence of session order or recovery time between training in soccer players. McGawley and Andersson (2013) examined the training order effect over a 5-week pre-season in a combination of semi- and full-professional players (*n* = 18) competing in a Swedish first division team. One group performed HIIT followed by resistance training (HIIT-RES, *n* = 9), while the other group completed resistance training followed by HIIT (RES-HIIT, *n* = 9). The order of training was manipulated three times per week and the content of the HIIT and RES training sessions varied throughout the experimental period, were always performed back-to-back (i.e., no between-session recovery time), and performed on top of normal technical and tactical training. Whilst both groups improved performance measures (10 m sprint, 1.8 ± 2.6%; 6 × 30 m repeated sprint, 1.3 ± 1.8%; agility, 1.0 ± 1.5%; and Yo-Yo test, 19.4 ± 23.4%), there were no between-group differences. However, as this study was performed over the pre-season period, performance improvements would be expected as the players returned to structured training following an off-season break. In addition, as recovery time between sessions has been shown to affect the training response (Sale, 1990; Robineau et al., 2016; Lee et al., 2020), the lack of recovery time between HIIT and resistance training may have influenced the results.

Another study in soccer players by Enright and colleagues (2015) studied the order effect of soccer and resistance training in 15 elite youth players during the first 5 weeks of the in-season period. The players performed two concurrent training days in the microcycle, with an additional two football sessions and a competitive match. Players were split into two groups, with the order of resistance (RES) and soccer training manipulated on the concurrent training days (RES-soccer, *n* = 8; soccer-RES, *n* = 7). Training content was consistent for both groups, with soccer training on the concurrent days consisting of a dynamic warm-up (~20-min), a possession-based SSG (4 vs 4, 4 x 4-min, 3-min active recovery), then varied technical and tactical work (~50-min). The resistance training session was strength-based and consisted of 4 sets of 6 repetitions at 85% of 1RM of the parallel back squat, deadlift, Romanian deadlift, and lunge, along with 3 sets of 8 repetitions of the Nordic hamstring exercise. Whilst both training groups improved most markers of neuromuscular performance after the training intervention, the soccer-RES group outperformed the RES-soccer group over a range of performance tests (e.g., CMJ height, 10 m sprint, 30 m sprint, half back squat 1RM, along with several other isokinetic and isometric measures), with *moderate-large* effect sizes. However, the results may be explained by the between-group differences in the recovery time between training sessions, and nutrient timing, as opposed to the order of training. Here, the RES-soccer group only had

~30 – 45-min of recovery between training sessions and were provided with a protein shake (220 kcal, 25 g protein, 13 g carbohydrate, 0.5 g fat) in this window. Opposingly the (soccer-RES group) had 2 hours of recovery between sessions and consumed a nutrient-dense meal (~1000 kcal, ~140 g carbohydrate, ~60 g protein, ~25 g fat) in the 2-hour period between training sessions. Whilst it is possible that signalling pathways (e.g., mTOR) from the RES-soccer group may have been blunted by the endurance-based soccer training performed after the strength training, it is very likely that the differences in the between-session recovery time and the nutrient intake confounded the results. Nevertheless, this study has high ecological validity, and these challenges are likely a situation many soccer teams encounter when designing training schedules.

Taking the results of the studies mentioned above together, it seems that the interference effect of same-day concurrent training may be somewhat attenuated when sufficient recovery time is given between training sessions. In previous literature where multiple daily training is scheduled, between-session recovery times have varied from 0 – 6 hours (Nelson et al., 1990; Kraemer et al., 1995; Cook et al., 2014; Johnston et al., 2016; Russell et al., 2016; Fyfe et al., 2016; Robineau et al., 2016; Chtara et al., 2008; Lee et al., 2020). Johnston et al. (2015a) studied the responses to a maximal speed training session in elite rugby players and reported that whilst neuromuscular function immediately declined, there was a temporary recovery after 2 hours, before a secondary decline at 24 hours post. This bimodal recovery pattern has also been observed after marathon running (Avela, et al., 1999), intermittent team sports such as AFL (Cormack, Newton, & McGuigan, 2008) and soccer matches (Andersson et al., 2008). In addition, two studies discussed in section 2.6.1 of this review reported that compared to control trials, afternoon neuromuscular performance was improved following a morning resistance training session when 6 hours of recovery was given between sessions (Cook et al., 2014; Russell et al., 2016a). As discussed earlier in this review, this is likely to be a result of maintained T concentrations as a result of the morning weight training. Therefore, it seems that when multiple training sessions are performed on the same day, the performance of the second training session may not be diminished, or even improved when taking advantage of this bimodal recovery pattern. However, this is very likely dependent on the mode, volume and intensity of the exercises performed. It remains to be seen if combined resistance and SSG training produces a similar response, and importantly, it is not well understood which order or sequence of concurrent training is optimal in soccer.

2.8.5 Summary of the previous responses to training

This section has reviewed the published data on the acute responses to soccer training but the quantity of literature in this area is very limited. Taking the three reviewed studies in this area together, it seems as though the manipulation of the work to rest ratio of training and consequently, the within-training physical demands and physiological response may acutely influence the hormonal and neuromuscular pattern in response to training. Furthermore, it seems that CMJ height is a sensitive marker in detecting the responses to high-intensity soccer training sessions and may be compromised until 48 hours post-training. In contrast, research is abundant concerning the acute metabolic, neuromuscular, and endocrine responses to resistance training, however, there are large variations in the participants recruited, the training volume, intensity, and exercise selection. Whilst manipulation of these variables can result in varied adaptations, it seems that performance of training aimed at hypertrophic adaptations results in the greatest metabolic disruption, along with significant increases in T but with a concomitant increase in C. That said, it seems that training aimed at the development of strength is likely to evoke an anabolic response but to a lesser extent than hypertrophy training and may also take longer to recover from than hypertrophy or power training, which is possibly due to a greater CNS demand.

The challenges of creating concurrent training programs have been highlighted and the factors that may influence the interference effect have been reviewed. Here, it seems that strategically manipulating the within-day organisation of training may somewhat mitigate the interference effect. Moreover, despite the time-efficiency of scheduling resistance and endurance training back-to-back, this seems to be sub-optimal for both training performance and adaptations (Sale et al., 1990; Fyfe et al., 2016). Instead, if programming multiple daily training sessions, a strategy of allowing a longer between-mode recovery time should be adopted (e.g., 2 – 6 hours). This may minimise the potential opposing physiological mechanisms that promote endurance and resistance adaptations. Furthermore, this may reduce residual fatigue impairing training performance and take advantage of a bimodal recovery pattern of neuromuscular function that has been previously observed (Johnston et al., 2015). Considering the survey published by Cross et al. (2019) revealed that 92% of soccer teams reported scheduled resistance training following field-based training, it remains to be seen if changing the session order would result in different fatigue and recovery profiles. This may potentially impact the performance of training in the hours and days that follow, and support decision making on the within-day planning of concurrent training in soccer.

2.9 CHAPTER CONCLUSIONS

The opening section of this literature review (section 2.2) was written to provide a foundation for the following sections by reviewing the literature on the demands of competitive soccer. It is clear that soccer performance is underpinned by a dynamic interaction between physical, physiological, psychological, technical and tactical factors (Rampinini et al., 2008). It is likely that if there is a deficiency in one or more of these factors then performance will be compromised.

With regards to the physical demands of matches, there is a significant variation across playing positions for total, HSR and sprinting distances, with CDs having the lowest and highest running and combative demands respectively, CMs covering the most total distance and wide or attacking players (i.e., FB, WM and FW) covering more distance at HSR and sprinting speeds (Barros et al., 2007; Di Salvo et al., 2007; Bradley et al., 2009; Di Salvo et al., 2009). Interestingly, current research indicates that in professional leagues there seems to be no relationship between physical outputs and success across a season, and in fact, lower-ranked teams may be required to perform more distance, HSR and sprinting due to the more successful teams imposing their style of play on the opposition and retaining more possession of the ball (Rampinini et al., 2009a; Di Salvo et al., 2009; Bradley et al., 2013). However, as the playing standard increases across leagues and within leagues, the technical demands are higher, which is a better indicator of team success (Rampinini et al., 2009a; Di Salvo et al., 2009; Bradley et al., 2013). This highlights the complex nature of running demands in soccer, and since research shows there is a generally a decline in the performance of technical skills over the course of a match (Rampinini et al., 2008; Rampinini et al., 2009a), and that injury rates are higher towards the end of both halves (Price et al., 2004; Ekstrand, Hagglund, & Walden, 2011), it is plausible to suggest that having well-developed physical qualities may attenuate these negative outcomes.

Regarding the physiological demands of soccer, due to the length of a match (≥90-min) and the prolonged periods of low-intensity activity, the aerobic system is the predominant energy pathway with ~90% of a player's energy provided by aerobic metabolism (Stølen et al., 2005). However, the game outcome is often determined by explosive and powerful actions (e.g., kicking, tackling, accelerating, decelerating, sprinting, jumping, and changing direction), therefore well-developed anaerobic energy systems are also key (Helgerud et al., 2001; Stølen et al., 2005; Faude, Koch, & Meyer, 2012). A well-developed aerobic capacity underpins recovery between the above mentioned repeated anaerobic key game demands, and further, the high-intensity activities are underpinned by strength and power (Stølen et al., 2005). Interestingly, comprehensive studies with large sample sizes reveal that VO_{2max} in soccer players has remained relatively stable over the last four decades (Shalfawi & Tjelta, 2016), yet HSR and sprinting distances have increased significantly in recent years (~30 – 50%), along with the number of technical actions (i.e., passes, successful passes), which may represent a shift in training activities and/ or player recruitment strategies (Barnes et al., 2014).

As a result of the above-mentioned key game demands and physiological requirements, due to often-limited training time between fixtures as well as the long and demanding competitive season, training methods that simultaneously train the multiple targeted qualities may be favourable to optimise training time (Morgans et al., 2014; Walker & Hawkins, 2017). This has resulted in the use of SSGs being a very popular training modality, as they are thought to replicate some of the multiple requirements necessary (Reilly & White, 2004; Hill-Haas et al., 2011; Aguiar et al., 2012). Indeed, many previous studies have shown that some formats of SSGs can provide a potent physiological stimulus that can result in similar adaptations to various modes of traditional interval training and replicate or overload the physical demands of matches, whilst simultaneously working with the ball and maintaining interactions between team-mates and the opposition (Reilly & White, 2004; Hill-Haas et al., 2011; Aguiar et al., 2012). However, as detailed in section 2.3, the format of an SSG can be manipulated by a plethora of variables that can influence the physical demands and subsequently, the physiological responses and adaptations. Despite the fatigue and recovery time course from matches being studied extensively (e.g., Nedelec et al., 2012; Silva et al., 2018), there is very limited research on the impact of SSG training on fatigue and recovery markers, which may have important implications for their placement within the training week. To date, the only study that has assessed the acute hormonal responses to isolated SSG training was performed by Chmura et al. (2019), however, they only studied the T and C responses to 1 vs 1 SSG training up to 30-min post-exercise. The authors concluded that a longer recovery time between SSG repetitions reduced the immediate catabolic response in this cohort of u-18 soccer players. However, the endocrine, neuromuscular, biochemical, or perceptual responses to other formats of SSG over a longer period (e.g., 24 hours) is unknown.

Section 2.4 reviewed the literature on how the external physical demands of soccer are typically quantified. Conclusions from this section were that newer GPS devices sampling at a frequency ≥10 Hz are acceptable in detecting most sport-specific movements. However, some limitations may still exist when quantifying high-intensity accelerations and decelerations (Akenhead et al., 2014), or when comparing between different tracking systems or GPS devices (Cook, 2014; Buchheit et al., 2014b; Thornton et al., 2018; Linke et al., 2018). Furthermore, there are substantial variances between studies on the definitions, thresholds, and sampling frequency of GPS derived metrics, therefore caution should be used when comparing between previous studies. Nevertheless, this section identified a metric in Playerload^{TM}, derived from the 100 Hz accelerometer, that seems to be stable, reliable, and valid in quantifying global external load in team sport (Barrett et al, Midgley, & Lovell, 2014).

Whilst section 2.5 reviewed the literature on neuromuscular fatigue and identified the specific central and peripheral mechanisms that may be responsible for a loss of performance, section 2.7 has revealed that may be limitations in using laboratory-based measures in conjunction with isometric contractions in applied environments. For example, Requena et al. (2009) demonstrated that maximal force during isometric and isokinetic contractions may not reflect the performance of more functional, dynamic markers of soccer performance. Other authors have shown that there may be differences in the post-exercise recovery rates between different contraction types (Byrne & Eston, 2002; Andersson et al., 2008; Beneka et al., 2013; Kennedy & Drake, 2018). Both factors may limit the usefulness of isometric or isokinetic contractions for practitioners and coaches, who are likely to be more interested in assessing the ability of an athlete to undertake dynamic and explosive movements that are similar to the demands of the sport. Given this, it was concluded from the review that CMJ performance is an appropriate, non-invasive, and easy to administer marker to monitor neuromuscular fatigue, as exercises involving the SSC are sensitive to metabolic, mechanical, and neural elements of fatigue (Nicol, Avela, & Komi, 2006; Claudino et al., 2017). Furthermore, CMJ performance has been shown to have significant relationships with linear acceleration in a range of team sport athletes including soccer players (Wisloff et al., 2004; Northeast et al., 2019), success in key technical actions (Wing, Turner, & Bishop, 2018), final league standing over a season (Arnason et al., 2004), and is sensitive in assessing the neuromuscular response to soccer (Russell et al., 2016b; Thomas et al., 2017; Brownstein et al., 2017).

Strength and power are key qualities for soccer players to possess for several reasons, such as:

- Underpinning the performance of the repeated key anaerobic game demands (Wisloff et al., 2004; Helgerud et al., 2011; Silva, Nassis, & Rebelo, 2015).
- Improving the success rate in key technical actions (i.e., heading and tackling) (Wing, Turner, & Bishop, 2018).
- Improvements in RE (Hoff & Helgerud, 2003).
- Accelerating the recovery kinetics after matches (Owen et al., 2015).
- Reduction in incidence and severity of injury (Lehnhart et al., 1996; Folland & Williams, 2007; Opar et al., 2015), which has been shown to positively affect team performance over a season (Hagglund et al., 2013; Carling et al., 2015).
- Maintenance of neuromuscular performance over the course of a season (Koundourakis et al., 2014).
- Elevation of endogenous androgens, both acutely and chronically, which may promote numerous beneficial short-term performance effects and long-term adaptations as discussed in section 2.6 (Cook & Crewther, 2012a; Cook & Crewther, 2012b; Cook et al., 2014; Koundourakis et al., 2014; Russell et al., 2016a).

Whilst numerous resistance training programs have been used in previous literature, as power is fundamentally the product of force and velocity, it is suggested that heavy multi-joint resistance training aimed at the development of strength (i.e., ≤6 repetitions; ≥80% 1RM; ≥3-min recovery) or explosive training (e.g., ballistic exercises, plyometrics, velocity-based training, weightlifting derivatives) are the most appropriate training modalities for soccer players (Silva et al., 2015). However, one cannot express a high level of power without first being relatively strong, and a foundation of strength is, therefore, crucial for the long-term development of power (Cormie, McGuigan, & Newton, 2011b). It is recommended that one resistance training session per week is sufficient in maintaining strength during the in-season period, and two sessions per week may be necessary for significant improvements (Ronnestad, Nymark, & Raastad, 2011; Koundourakis et al., 2014; Turner & Stewart, 2014). However, this creates an important consideration for those responsible for the design of soccer training programs, as a large body of research indicates that the simultaneous integration of resistance and endurance exercise into a training program may compromise the development strength and power (Hickson, 1980; Leveritt et al., 1999; Wilson et al., 2012; Fyfe, Bishop, & Stepto, 2014). Nevertheless, it is well accepted that concurrent training programs should be implemented in soccer in order to optimise performance, therefore practitioners should consider the factors that may mitigate the interference effect. It has been shown in section 2.8.4 that training session order and between-session recovery time may be important factors to consider. However, there is very limited research on the interaction between same-day field and resistance training in soccer, despite this being a very common occurrence (Cross et al., 2019).

2.10 RESEARCH AIMS AND OBJECTIVES

After reviewing the literature in soccer and establishing gaps in our current understanding of SSG training and its scheduling within a concurrent training program, the research questions this thesis hopes to answer have been established. These will be investigated over a series of three experimental studies with differing aims and objectives but aligned to the same overall topic. The specific aims and objectives of the studies are the following:

- The primary aim of chapter 4 is to profile the neuromuscular, endocrine, biochemical and mood responses to SSG training over a 24-hour period. Additionally, this study will observe the pattern of the between-repetition changes in physical demands during SSG training. The specific questions this study will aim to answer are:
    - What pattern do the external demands of the SSG training follow across repetitions?
    - What is the impact of this mode of training on the immediate neuromuscular, biochemical, endocrine, and mood responses?
    - What pattern do the markers highlighted above follow over 24 hours?
    - How may this impact the scheduling of SSG training and their interaction with additional activities throughout a training program?

- The aim of chapter 5 is to compare the neuromuscular, endocrine and mood responses to a day consisting of SSG training (single session) vs a day consisting of SSG training plus resistance training 2 hours later (double session). Specifically, this study will aim to answer the following questions:
    - Does the performance of a double training session result in further fatigue on the following day of training?
    - How might this impact the scheduling of training in soccer?

- Finally, chapter 6 will aim to establish the acute effects of manipulating the order of SSG and resistance training. The questions this study will aim to answer are:
    - What effect does the order of training have on the neuromuscular, endocrine and mood responses over a 24-hour period?
    - Does the order of training affect the performance of either training session?
    - How might this affect training on the following day?

Chapter 3.

General Methods

3.1 INTRODUCTION

This thesis features a series of three studies which were designed to investigate the responses to SSG and resistance training and the optimisation of their placement and sequencing within a training week. Whilst a range of different study designs were implemented to achieve this, there was an overlap between some of the methods used across the experimental chapters. Therefore, this chapter will describe those methods that were repeated to avoid excessive replication of text throughout the thesis.

3.2 PARTICIPANTS

Participants were recruited from an EPL under-23 team in chapter 4, and from a semi-professional soccer team in chapters 5 and 6. Participant characteristics had minor variations between studies and are detailed in each chapter. Despite the use of GKs during the SSG protocol, only data from outfield players were included in the analyses. All participants were considered healthy and injury-free during the period of each study. Each participant was provided with an information sheet that detailed the risks and benefits of involvement, as well as explaining that their inclusion was entirely voluntary and that they had the right to withdraw at any moment (Appendix 1). If the athletes opted in, they provided written informed consent before participation in the study (Appendix 2). Ethical approval was granted by the ethics advisory board of Swansea University (Appendix 3). All participants had a substantial experience and training history in both soccer (>5 years) and resistance training (>2 years).

3.3 TRAINING SESSIONS

Each of the three experimental chapters implemented the same SSG protocol. Additionally, in chapters 5 and 6 participants performed a resistance training session. Both the SSG and resistance training sessions are described in detail below.

3.3.1 Small-sided games

After a standardised 5-min warm-up consisting of mobility exercises, dynamic stretching and short sprints, players were split into teams of five (4 vs 4 +GKs) by coaching staff. The teams were organised such that the playing positions were balanced within each team (e.g., 1 GK, 1 CB, 1 FB or 1WM, 1 CM, and 1 FW). The sports surface was a modern third generation artificial grass pitch and players wore their normal training footwear during the SSG. Timings were strictly controlled, and players were instructed to play against another team for 6 repetitions of 7-min (SSG play, 42-min) with 2-min between each repetition allowed for players to passively rest and consume water ad libitum before the next repetition. Total training time from the start of the warm-up to leaving the field was 1-hour, which was comparable to the duration of a typical training session in this cohort of players. Pitch size was 24 x 29 m (width x length), and full-sized regulation goals were used (width x height; 7.32 x 2.44 m). Players were allowed unlimited touches of the ball and the aim was to score more goals than the opposition (i.e., win the game). Team coaches were present to provide encouragement and balls were readily available for replacement when the ball went out of play intending to maintain the SSG intensity (Rampinini et al., 2007c; Sampaio et al., 2007; Halouani et al., 2014).

As reviewed in section 2.3.2, there is an abundance of literature on the use of SSGs, and how manipulation of the structural format can influence the intensity. After careful consideration with regards to the factors illustrated in Figure 4, and discussion with the team coaches (UEFA pro-licence holders), the structural format of the SSG was selected for several reasons. Firstly, to limit artificial design, the SSG format complemented the players normal training regimes. Secondly, the number of players (4 vs 4 +GKs), the absolute area size (24 x 29 m; width x length) and the relative area size per player (87 m) were similar to those used in an abundance of previous studies (Reilly & White, 2004; Sassi, Reilly, & Impellizzeri, 2004; Impellizzeri et al., 2006; Little & Williams, 2007; Rampinini et al., 2007c; Dellal et al., 2008; Kelly & Drust, 2008; Hodgson, Akenhead, & Thomas, 2014; Hulka, Weisser, & Belka, 2016; Beenham et al., 2017; Lacome et al., 2018). Thirdly, the training prescription (6 x 7-min; overall work time, 42-min) was within the guidelines suggested by previous authors (Hill-Haas et al., 2009a Hill-Haas et al., 2009c; Moran et al., 2019). Finally, the use of GKs and regulation goals were included to retain the structural format of the team and replicate the characteristics of competitive match-play (Dellal et al., 2008).

3.3.2 Resistance training session

The content of the lower body resistance training session was selected to include exercises, volumes and intensities the participants were familiar with, whilst also being within the guidelines for strength development (Kraemer, Duncan, & Volek, 1998; Beaven, Cook, & Gill, 2008; Johnston et al., 2016). Specifically, the session consisted of 4 sets of 4 repetitions of the parallel back squat, the Romanian deadlift, and the barbell hip thrust. Each exercise was performed at 85% of 1RM with 4-min recovery between sets and exercises. As a warm-up, each exercise was preceded by 2 sets of 4 repetitions at 50% and 70% of 1RM. Rest periods were strictly controlled, and the training session lasted 1-hour. To ensure appropriate technique was maintained throughout, the training session was supervised by an accredited strength and conditioning coach (United Kingdom Strength & Conditioning Association; UKSCA). To determine the individual training intensities (i.e., 85% 1RM), each participant was required to perform a 3RM test of each exercise that occurred one week prior to the experimental protocol. Then, 1RM was calculated based on the 3RM data, with a commonly used equation developed by Brzycki (1993). Specifically, this equation was the following: weight lifted ÷ (1.0278 – [0.0278 × number of repetitions]). This equation has been shown to have strong relationships between predicted and actual 1RM over a range of exercises (r >0.90), in similar population groups to those recruited in the current thesis (Mayhew et al., 1995; LeSuer et al., 1997; DiStasio, 2014). A 3RM test was chosen to diminish the possible risk of technique breakdown or injury associated with maximal loads (Madsen & McLaughlin, 1984; Mayhew et al., 1992).

3.4 PHYSICAL DEMANDS

The physical demands of the training sessions were measured using the same methods across the experimental chapters, which are described below.

3.4.1 Time-motion analyses

The movement demands of each SSG were recorded using the same GPS device (OptimEye S5, Catapult Innovations, Melbourne, Australia). These devices sample at 10 Hz and are embedded with a 100 Hz tri-axial accelerometer (Figure 7). As reviewed in section 2.4.3 of this thesis, these units have been shown to hold acceptable inter and intra-unit reliability as well as good validity when tracking team-sport movements (Varley, Fairweather, & Aughey, 2012; Cummins et al., 2013; Johnston et al., 2014). Furthermore, this model of GPS device has passed a quality control experiment carried out by FIFA and is listed on their official website as meeting or exceeding the industry standard for electronic performance tracking systems. Each participant wore the same GPS device over time as recommended in prior literature (Scott et al., 2015; Thornton et al., 2019). Units were positioned between the scapulae in a neoprene undergarment with an integrated pouch supplied by the manufacturer (Figure 6). Data were downloaded and processed automatically using the manufacturer software (Openfield, Catapult

Innovations, Melbourne, Australia). As discussed in section 2.4.6 and demonstrated in Table 7, there is a wide range of thresholds used for the detection of HSR in previous literature. The thresholds used in this thesis matched the daily monitoring of the specific team studied and were set in line with many previous studies in soccer (Harley et al., 2010; Thorpe & Sunderland, 2012; Akenhead et al., 2013; Gaudino et al., 2013; Scott et al., 2013; Akenhead et al., 2014; Russell et al., 2016b; Russell et al., 2016c; Ehrmann et al., 2016; Anderson et al., 2016; Owen et al., 2017b; Lacome et al., 2018; Harper, Carling, & Kiely, 2019). Operational definitions for each of the GPS derived metrics across the experimental chapters are displayed in Table 9. A survey completed by 41 practitioners from elite soccer teams ranked each of these variables in the top 10 for perceived importance when monitoring training load (Akenhead & Nassis, 2016).

Table 9. Operational definitions used to define the GPS variables included in this thesis.

Variable (abbreviation)	**Definition**
Total distance	Distance covered (m) by all means of locomotion.
High-speed running (HSR)	Total distance (m) covered at a velocity ≥5.5 $m \cdot s^{-1}$ (or ≥19.8 $km \cdot h^{-1}$).
Playerload™	Vector magnitude that accumulates the total acceleration in three planes of movement (vertical, anterior-posterior and medio-lateral). Refer to section 2.4.5 for more detail.

3.4.2 Rating of perceived exertion

To obtain a subjective marker of training load for the training sessions, each participant was asked to select an RPE on a modified version of the Borg CR-10 scale (Borg, 1982; Foster et al., 2001). Category ratios ranged from 0 – 10, witch scale anchors ranging from ‘rest’ to ‘maximal’. Values for RPE were obtained ~30-min after the cessation of exercise and in isolation from team-mates in order to avoid possible peer influence (Minett et al., 2021).

Players were familiar with this scale as part of their normal training programs and it has been used extensively in prior literature (Rampinini et al., 2007c; Casamichana & Castellano, 2010; Köklü et al., 2013; Hulka, Weisser, & Belka, 2016). The CR-10 scale has been shown to have strong relationships with HR based markers of training load in soccer (Impellizzeri et al., 2004; Alexiou & Coutts, 2008; Coutts et al., 2009). Furthermore, many studies have validated the CR-10 scale for the measurement of the intensity of resistance exercise (Sweet et al., 2004; Day et al., 2004; Buckley & Borg, 2012; Morishita et al., 2018).

3.5 NEUROMUSCULAR FUNCTION

In each experimental chapter, after neuromuscular function was assessed with a portable FP with a built-in charge amplifier (Type 92866AA, Kistler Instruments Ltd., Farnborough, United Kingdom). After confirming calibration and following previously established procedures (Owen et al., 2014; West et al., 2014a; West et al., 2014b; Russell et al., 2016b; Birdsey et al., 2019), vertical ground reaction forces (VGRF) were sampled at 1000 Hz through a 16-bit analogue to digital converter (Kistler Instruments Ltd., Farnborough, United Kingdom) using Kistler's Bioware (version 3.2.7.0). A standardised 5-min warm-up consisting of dynamic movements with emphasis placed on the lower body musculature was performed prior to each jump test, with the exception of time points whereby the athletes had just finished training, at which one practice CMJ was performed. The participant was then instructed to stand as still as possible on the FP, at which point they indicated they were ready to begin, and sampling was initiated (Street et al., 2001). After a minimum period of two seconds, each participant performed a CMJ, during which they were encouraged to gain maximum height. Depth was self-selected by the participants and in order to isolate the lower limbs, participants kept hands-on-hips throughout the jump (Owen et al., 2014). A period of 90 s rest was then given, after which the participants repeated the CMJ procedure. Bodyweight was taken to be the mean value of the vertical vGFR during the first second of data collection (Owen et al., 2014). Three variables were then calculated from the data using a previously established criterion method (Owen et al., 2014). The first, peak-power output (PPO) was determined by multiplying the force collected at each sampling point by its corresponding velocity and identifying the highest value. The second, relative PPO ($W \cdot kg^{-1}$) was calculated by dividing PPO by the participants bodyweight in kg. Finally, JH (cm) was calculated from take-off velocity and defined as the difference between vertical displacement at take-off and maximal vertical displacement. Test-rest CV values for PPO and JH were 2.3% and 3.2%, respectively. For both PPO and JH, the peak value of the two trials was used in the statistical analyses.

3.6 HORMONAL ANALYSES

For salivary hormone analysis, participants were instructed to avoid eating or drinking fluids other than water in the 1-hour prior to testing to avoid contamination of samples. Replicating previously established methods (e.g., Cook et al., 2012a; Crewther et al., 2013; Birdsey et al., 2021), two millilitres (ml) of saliva were collected by passive drool into sterile containers, then stored at -80°C until assay. After thawing and centrifugation (2000 rpm x 10-min), the saliva samples were analysed in duplicate for T and C concentrations using commercial kits (Salimetrics LLC, USA). Assay plates were read by a micro-plate reader (Biohit BT800, Helsinki, Finland). The minimum detection limit for the T assay was 6.1 $pg{\cdot}ml^{-1}$ with an inter-assay CV of 5.8%. The C assay had a detection limit of 0.012 $ug{\cdot}dl^{-1}$ with an inter-assay CV of 5.5%. Samples for each participant were assayed in the same plate to eliminate inter-assay variability. Salivary concentrations of T and C are often used as a non-invasive surrogate for blood samples and frequently reported to have very high correlations with serum concentrations ($r > 0.90$; Nahoul, Rao, & Scholler, 1986; O'Connor & Corrigan, 1987; Neary, Malbon, & McKenzie, 2002; Dorn et al., 2007). In addition, salivary measures of T and C are independent of saliva flow rate (Riad-Fahmy, Read, & Walker, 1983).

3.7 MOOD ASSESSMENT

Mood state was assessed using a modified version of the brief assessment of mood questionnaire (BAM+; Appendix 4; Shearer et al., 2017). This 10-item questionnaire is based on the POMS assessment and consists of a scale where players mark on a 100-millimetre scale about how they feel at that moment in time. Scale anchors ranged from 'not at all' to 'extremely' and the participants marked a vertical line on the scale at the point that described how they felt at that moment time. The questions assess the following mood adjectives: anger, confusion, depression, fatigue, tension, alertness, confidence, muscle soreness, motivation, and sleep quality (Appendix 4). Players completed the questionnaires in isolation from teammates, and it took ~1-min to complete. The scores were totalled up into a composite score of mood by giving the six unfavourable questions a positive value, and the four favourable questions a negative value. Total mood scores initially ranged from -40 – 60, before adding 40 to each score so that the scale ranged from 0 – 100, with 0 indicating the best and 100 indicating the worst mood. This method of calculating mood has been shown to have acceptable internal consistency, with Cronbach's alpha scores for the four positive ($\alpha = 0.65$) and the six negative items ($\alpha = 0.82$) indicating reasonable internal consistency and that items were grouped correctly (Shearer et al., 2017). Across five games in EPL u-21 soccer players, moderate and significant ($p < 0.01$) correlations have been reported between match activity (total distance per minute, $r = -0.474$; HSR per minute, $r = -0.441$ and number of sprints per minute; $r = -0.551$) and changes in BAM+ at 24 and 48 hours post-match (Shearer et al., 2017). Furthermore, it has been shown to be sensitive to physiological responses following both elite soccer (Shearer et al., 2017), and netball competition (Birdsey et al., 2019).

3.8 STATISTICAL ANALYSES

Due to variations in statistical methods being used across the experimental chapters, the specific methods will be described in each chapter.

Chapter 4.

The Neuromuscular, Biochemical, Endocrine and Mood Responses to Small-Sided Games Training in Professional Soccer Players

4.1 INTRODUCTION

Soccer is a prolonged intermittent sport that involves periods of high-intensity linear and multidirectional activity interspersed with lower intensity activity, as well as technical and tactical components (Bangsbo, Mohr, & Krustrup, 2006; Rampinini et al., 2007b; Carling et al., 2008). Due to the multifaceted game demands, soccer players are required to train multiple physical qualities, including but not limited to strength, power, speed, agility, aerobic capacity, RSA, as well as engage with technical and tactical training (Stølen et al., 2005). As there is often limited training time between fixtures, time-efficient methods of simultaneously developing these multiple qualities are desirable (Morgans et al., 2014). This usually results in concurrent training methods, with multiple sessions often undertaken on the same day and within 24 hours of each other (Malone et al., 2015a; Martín-García et al., 2018b; Cross et al., 2019). For an athlete to positively adapt to training, the stimulus should be applied in an order or a spacing that allows recovery to a point where they are able to meet the demands of the following activity (Bishop, Jones, & Woods, 2008). Therefore, practitioners require an understanding of the demands and responses to each activity a player performs throughout a training program.

A very popular training method in applied settings and previous soccer literature is SSGs; utilised by coaches to optimise training time as they are thought of as being able to replicate the demands of competition (Dellal et al., 2008; Hill-Haas et al., 2011; Brandes, Heitmann, & Müller, 2012; Casamichana, Castellano, & Castagna, 2012). Indeed, SSGs are used extensively to improve and maintain physical fitness along with technical and tactical performance in professional soccer players (Hill-Haas et al., 2011; Morgans et al., 2014). Previous attempts to characterise the internal and external demands of SSGs have been achieved via the collection of HR, movement demands (e.g., GPS data), BLa, and perceptual (e.g., RPE) responses (Hill-Haas et al., 2011). Whilst numerous studies have shown that manipulating variables such as the playing area, the number of players and the rules of the game can influence the acute physiological response (Hill-Haas et al., 2011; Brandes, Heitmann, & Müller, 2012; Casamichana, Castellano, & Castagna, 2012), it is not well understood what impact the performance of SSGs may have in the hours and days that follow. A greater understanding of this may be of interest to those responsible for the design of soccer training programs, given the possible influence that this may have on additional training sessions performed within the week.

Typically, SSGs are programmed in a similar format to intervals, with a set number of repetitions and standardised recovery periods. Previous studies have shown that changes between repetitions during the same SSG training session may show a metric dependent variability, which is independent of the number of players (i.e., 1 vs 1 – 7 vs 7), task constraints (e.g., touch limitations) and playing level (e.g., amateur vs professional) (Clemente et al., 2021). Within this area, studies have shown that total distance and accelerometry derived variables are relatively stable, with *small – moderate* changes between the lowest and highest repetitions (~1 – 10%). In comparison, high-speed efforts are reported to have *large* between-repetition changes (~35 – 400%) (Dellal et al., 2011b; Dellal, Drust, & Lago-Penas, 2012; Clemente et al., 2017; Clemente et al., 2019b; Clemente et al., 2020; Bujalance-Moreno et al., 2020; Younesi et al., 2021). Of these studies, only four have recruited professional players, therefore further research in this area may be beneficial to broaden our understanding of the within-session changes and temporal activity patterns during SSGs in professional players.

Numerous studies have previously examined the acute post-exercise responses induced by soccer match-play (e.g., Andersson et al., 2008; Rampinini et al., 2011; Nedelec et al., 2012), strength training (e.g., Hakkinen, 1992; Bosco et al., 2000; Beaven, Gill, & Cook, 2008; McCaulley et al., 2009;), speed training (Johnston et al., 2015a), and endurance training (e.g., Daly, 2005; Petersen et al., 2007). It is well known that any repeated eccentric or SSC actions, which are prevalent in soccer, have the possibility of inducing muscle damage (Dousset et al., 2007), soreness (Burt et al., 2014) and reducing neuromuscular performance (Nicol, Avela, & Komi, 2006). Therefore, measures of neuromuscular function and markers of muscle damage are often used to assess fatigue and recovery from soccer-specific exercise (Nédélec et al., 2012). In addition, the hormones T and C have drawn particular focus in previous literature due to their functions in regulating anabolic and catabolic activity and their influence on acute and chronic changes in performance and adaptations (Teo, McGuigan, & Newton, 2001; Spiering et al., 2008b; Walker, Ahtiainen, & Hakkinen, 2010). Moreover, T and C have been shown to respond in distinct ways to various types of exercise, and the ratio between the two hormones has been reported as a marker of anabolic vs catabolic activity (Crewther et al., 2011b). Despite evidence suggesting these hormones may influence acute changes in the neuromuscular system, cognitive function, protein signalling and muscle glycogen synthesis (Cook, Crewther, & Kilduff, 2013; Gaviglio et al., 2014), the endocrine response to SSG activity is not well understood. In addition to objective markers, subjective questionnaires that aim to determine indicators such as athlete mood, muscle soreness, fatigue, sleep quality, stress, and motivation, are also widely used in team sports (Kellmann & Gunther, 2000; Akenhead & Nassis, 2016; Thorpe et al., 2017). These questionnaires are usually a practical and cost-effective means of monitoring and have been reported as a valid method of examining the dose-response relationship between exercise and fatigue (Thorpe et al., 2015; Shearer et al., 2016; Shearer et al., 2017).

To date, there is no comprehensive data on the magnitude of fatigue and the recovery time course in response to SSG training in soccer. Given the popularity of SSGs, and that physically demanding training sessions are often programmed on consecutive days in soccer, a greater understanding of the response to SSG training may be of interest to those responsible for designing soccer training programs. Therefore, the primary aim of this study was to characterise the neuromuscular, endocrine, metabolic and mood response to an SSG training session over a 24-hour period. A secondary aim was to observe the within-session changes in the external physical load across SSG repetitions.

4.2 METHODS

4.2.1 Experimental design

This study profiled the neuromuscular, endocrine, biochemical and mood responses to an SSG training session. The study took place towards the end of the 2015-16 competitive season with players being given 2 full rest days prior test involvement. Performance of CMJs (relative PPO, and JH), blood (CK, and BLa concentrations), saliva (T and C concentrations), and a brief assessment of mood (BAM+) were collected before (baseline), and after (immediately, 0h; 2 hours, +2h; 24 hours, +24h) the SSG training session. Objective and subjective training loads during the SSGs were obtained via 10 Hz GPS devices and RPE, respectively.

4.2.2 Participants

16 male professional soccer players (age, 20 ± 2 yr; mass, 74.8 ± 5 kg; height, 1.81 ± 0.06 m) who represented an English Premier League under-23 soccer team were recruited for this study. Players were in the maintenance phase of their training season, undertaking resistance training programs, team-based conditioning sessions, and technical and tactical training. On a typical microcycle consisting of 1 game·week^{-1}, players were undertaking 4 – 5 on-field training sessions and 1 – 2 resistance training sessions. Participants provided written informed consent before involvement and ethical approval was granted by the ethics advisory board of Swansea University (Appendix 1 – 3).

4.2.3 Procedures

On arrival at the training ground and before breakfast (~08:45 h), baseline salivary samples and BAM+ mood questionnaire scores were obtained. Players were then instructed to follow their normal breakfast routines as prepared for them at the training facilities. In a 30-min window prior to training (~09:45 – 10:15 h), a capillary blood sample was taken and CMJ testing was performed on a portable FP. The SSG training session began at 10:30 h and training load was monitored via GPS and RPE. Follow up measures (saliva, BAM+, blood, and CMJs) were collected at 0h, +2h and +24h post-training. In the 2-hour window between time points 0h and +2h, players consumed a nutritionally balanced lunch and drank water ad libitum as normally provided at the training facilities.

4.2.3.1 Small-sided games

The SSG format was standardised as described in chapter 3.3.1.

4.2.3.2 Time-motion analysis

Movement demands of the SSGs were recorded using 10 Hz GPS devices (Optimeye S5, Catapult Innovations, Melbourne, Australia). Metrics exported for analyses in this study were total distance, HSR and Playerload^{TM} as they aligned with the club monitoring strategy at the time of study and have been used extensively in previous literature. Please refer to chapter 3.4.1 for a detailed description of the time-motion analyses.

4.2.3.3 Rating of perceived exertion

Subjective markers of training load were obtained using the methods outlined in chapter 3.4.2.

4.2.3.4 Neuromuscular function

A portable FP (Type 92866AA, Kistler Instruments Ltd., Farnborough, United Kingdom) was used to measure neuromuscular performance of the lower body. Measures taken from the CMJ were relative PPO ($W \cdot kg^{-1}$) and JH (cm). For more detail, please refer to chapter 3.5.

4.2.3.5 Blood sampling

Blood samples were drawn at all time points during this study. After immersing the participants hand in warm water to promote blood flow, whole blood was collected via fingertip puncture using a spring-loaded disposable lancet (Safe-T-Pro Plus, Accu-Chek, Roche Diagnostics GmBH, Germany). First, a 5-μL sample of whole blood was taken for the immediate determination of BLa (Lactate Pro, Arkray, Japan). Next, a 300-μL sample was collected in a capillary tube and immediately centrifuged (Labofuge 400R, Kendro Laboratories, Germany) at 3000 rpm for 10-min for the extraction of 6-μL of plasma, which was subsequently analysed for CK using a semi-automated analyser (ABX Pentra 400; ABX Diagnostics, Northampton, UK). Testing of samples was carried out in duplicate and the mean CV for CK was 1.6%. Two participants were reluctant to have blood samples drawn, therefore, no samples were extracted for these two participants ($n = 14$).

4.2.3.6 Hormonal analysis

Salivary T and C concentrations were collected as per the methods outlined in chapter 3.6.

4.2.3.7 Mood assessment

Mood state was assessed using a modified version of the brief assessment of mood questionnaire (BAM+; Appendix 4). Please refer to chapter 3.7 for more detail.

4.3 STATISTICAL ANALYSES

Data are reported as mean ± SD. Visual inspection of the residual plots revealed no clear evidence of heteroscedasticity, therefore we performed all analyses on the raw untransformed data. Separate linear mixed models (SPSS v.21, Armonk, NY: IBM Corp) were used to examine the effect of SSG on our physical variables (total distance, HSR, and Playerload^{TM}), and also on our fatigue marker responses (mood score, CK, PPO, JH, T, C, and BLa). For these models, SSG (1 – 6) and time point (baseline, 0, +2h, and +24h), respectively, were entered as the fixed effect. In both models, players were included as a random effect with a random intercept to account for the hierarchical nature of our design (i.e., repeated measurements from the same players). Following this, a custom-made spreadsheet (Hopkins, 2007) was used to determine magnitude-based inferences for all differences, with inferences based on standardised thresholds for small, moderate, and large differences of 0.2, 0.6 and 1.2 of the pooled between-subject standard deviations (Hopkins, Marshall, & Batterham, 2009). The chance of the difference being substantial or trivial was interpreted using the following scale: 25–75%, possibly; 75–95%, likely; 95–99.5%, very likely; >99.5%, most likely (Batterham & Hopkins, 2008). The uncertainty in our estimates is expressed as 90% confidence limits (CL). We classified the magnitude of effects mechanistically, whereby if the 90% confidence limits overlapped the thresholds for the smallest worthwhile positive and negative effects the effect was deemed unclear (Hopkins et al, 2009).

4.4 RESULTS

4.4.1 Physical demands of the small-sided games

The GPS data for each SSG repetition, the difference between repetitions and the sum of all repetitions are presented in Table 10. The mean total distance covered during all the SSGs combined was 4388 ± 231 m. Between-repetition analyses revealed *moderate – large* reductions in total distance in all SSG repetitions in comparison to SSG 1. All other changes in total distance between SSG repetitions were *small* or *trivial*. The total HSR distance accumulated during the SSGs was 41 ± 30 m, with *moderate – large* reductions in HSR in all SSGs in comparison to SSG 1. All other changes in HSR between repetitions being *small* or *trivial*. The total Playerload^{TM} accumulated over the SSGs was 483 ± 38 AU. Whilst no large between-repetition differences in Playerload^{TM} were observed, there were *moderate* reductions in all SSGs in comparison to SSG 1. All other changes in Playerload^{TM} between SSGs were *small* or *trivial*. The mean RPE reported for the whole training session was 7.1 ± 1.3 AU, which is classified as 'very hard' on the scale used.

Table 10. Mean (± SD) physical variables across each SSG repetition during the training session, along with qualitative inferences of effect magnitude for all between-repetition comparisons.

	Game Number							
Variable	1	2	3	4	5	6	Total	Qualitative inferences for effect magnitude (mean difference; ±90% CL)
Total distance (m)	797 ± 36	736 ± 48	714 ± 42	705 ± 73	730 ± 60	704 ± 48	4388 ± 231	***Large***: 1v4**(-92; ±29), 1v6** (-93; ±19), 1v3*(-83; ±19) ***Moderate***: 1v5***(-67; ±31), 1v2** (-61; ±28) ***Small***: 2v4** (-31; ±37), 2v6** (-32; ±30), 4v5** (+25; ±39), 5v6** (-26; ±34), 2v3* (-22; ±30), 3v5* (+16; ±34), ***Trivial:*** 2v5 (-6; ±38), 3v4 (+9; ±32), 3v6 (-10; ±24), 4v6 (-1; ±32),
High-speed Running (HSR) (m)	15 ± 10	4 ± 4	5 ± 6	7 ± 9	6 ± 9	4 ± 5	41 ± 30	***Large***: 1v2* (-11; ±5), 1v6* (-11; ±4) ***Moderate***: 1v3** (-10; ±6), 1v4** (-8; ±7), 1v5** (-9; ±7) ***Small***: 2v4** (+3; ±4), 2v3* (+1; ±2), 2v5* (+2; ±5), 3v4* (+2; ±4), 3v6* (-1; ±5), 4v6* (-3; ±5), 5v6* (-2; ±4) ***Trivial:*** 2v6 (0; ±5), 3v5 (+1; ±5), 4v5 (-1; ±6)
Playerload^{TM} (AU)	86 ± 6	81 ± 9	80 ± 6	79 ± 8	80 ± 10	77 ± 7	483 ± 38	***Moderate***: 1v6*** (-9; ±3), 1v4** (-7; ±3), 1v2* (-5; ±5), 1v3* (-6; ±3), 1v5* (-6; ±4), ***Small***: 2v6** (-4; ±5), 3v6** (-3; ±3), 2v4* (-2; ±5), 3v4* (-1; ±3), 4v6* (-2; ±4), 5v6* (-3; ±4) ***Trivial:*** 2v3 (-1; ±5), 2v5 (-1; ±5), 3v5 (0; ±4), 4v5 (+1; ±4)

SD, standard deviation; SSG, small-sided game; CL, 90% confidence limits; AU, arbitrary units.

Magnitude-based inferences: *25-75%, possibly; **75-95%, likely; ***95-99.5%, very likely.

4.4.2 Neuromuscular function

Group mean data for relative PPO and JH are presented in Table 11. We observed a bimodal recovery pattern for both relative PPO and JH. There was an immediate decrease in JH at 0h (*possibly moderate*; -8.6 ± 12.4%), which returned to near baseline values at +2h (*trivial*; +0.2 ± 5.6%), before further impairment at +24h (*likely small*; -6.8 ± 6.3%). Similarly, relative PPO immediately decreased at 0h (*possibly small*; -2.1 ± 3.8%), which returned to near baseline values at +2h (*trivial*; +1.3 ± 3.6%), before further impairment at +24h (*possibly small*; -1.7 ± 3.4%).

4.4.3 Biochemical response

Group mean data for BLa and CK concentrations are presented in Table 11. In comparison to baseline, there was an immediate elevation in CK at 0h (*very likely small*; +40.6 ± 39.4%), which persisted at +2h (*possibly moderate*; +49.2 ± 47.6%), and at +24h (*very likely small*; +39.2 ± 51.6%). For BLa, there was an immediate increase at 0h (*likely large*; +100.2 ± 100%), before a decrease at +2h (*likely small*; -34.2 ± 20.9%), before returning to baseline at +24h (*trivial*; +5.9 ± 39.3%).

4.4.4 Mood questionnaires

The mean changes in mood scores across each time point are presented in Table 11. Relative to baseline, there was an immediate disturbance in mood at 0h (*likely moderate*; +47.2 ± 80.5%) which persisted at +2h (*likely small*; +27.4 ± 76.8%) but not +24h, where mood had returned to near baseline values (*trivial*; +8.7 ± 42.3%).

4.4.5 Hormonal response

The time course of changes in mean values for T, C, and the T:C ratio are presented in Table 11. *Concentrations of* T were immediately increased at 0h (*possibly small*; +11.1 ± 39.7%), before a reduction at +2h (*likely moderate*; -33.9 ± 27.3%) and a return to near baseline at +24h (*trivial*; +1.2 ± 52.8%). For C, there was an immediate decrease at 0h (*possibly small*; -16.5 ± 81.4%), with a further reduction at +2h (*likely large*; -71.8 ± 17.7%), which remained below baseline at +24h (*likely small*; -21.3 ± 40.9%). The T:C ratio was elevated across all time points in this study. Relative to baseline, the T:C ratio at 0h, +2h, and +24h was increased by 66.6 ± 81.4% (*possibly moderate*), 130.4 ± 101.7% (*likely large*), and 22.2 ± 54.2% (*possibly small*), respectively.

Table 11. Group mean (± SD) data for neuromuscular, endocrine, biochemical and mood markers across each time point, along with mean differences and qualitative inferences (QI) of the effect magnitude for differences from baseline values.

	Time point									
Variable	Baseline	0h	Mean difference from baseline; ±90% CL	*QI*	+2h	Mean difference from baseline; ±90% CL	*QI*	+24h	Mean difference from baseline; ±90% CL	*QI*
Mood score (AU)	28.8 ± 14	42.4 ± 16.5	+13.6; ±5.6	*M***	36.7 ± 12.8	+7.9; ±5.0	*S***	31.3 ± 16.3	+2.5; ±4.5	*T*
Creatine kinase ($\mu \cdot L^{-1}$)	239 ± 174	336 ± 214	+97; ±28	*S****	357 ± 195	+118; ±24	*M**	333 ± 128	+94; ±49	*S****
Blood lactate ($mmol \cdot L^{-1}$)	1.3 ± 0.5	2.6 ± 1.1	+1.3; ±0.5	*L***	0.8 ± 0.2	-0.5; ±0.2	*S***	1.4 ± 0.6	+0.1; ±0.2	*T*
Relative peak power output ($W \cdot kg^{-1}$)	53.1 ± 4.8	52.0 ± 4.2	-1.1; ±0.9	*S**	53.8 ± 4.9	+0.7; ±0.8	*T*	52.2 ± 4.4	-0.9; ±0.8	*S**
Jump height (cm)	37.1 ± 4.4	33.9 ± 6.5	-3.2; ±1.9	*M**	37.2 ± 4.6	+0.1; ±0.9	*T*	34.6 ± 3.8	-2.5; ±1.2	*S***
Testosterone ($pg \cdot ml^{-1}$)	181 ± 64	201 ± 71	+20; ±29	*S**	119 ± 41	-61; ±21	*M***	183 ± 50	+2; ±31	*T*
Cortisol ($\mu g \cdot dl^{-1}$)	0.54 ± 0.28	0.45 ± 0.29	-0.09; ±0.16	*S**	0.15 ± 0.06	-0.39; ±0.12	*L***	0.42 ± 0.16	-0.12; ±0.11	*S***
T:C ratio (AU)	371 ± 121	618 ± 415	+247; ±162	*M**	855 ± 340	484; ±143	*L***	453 ± 107	+82; ±54	*S**

SD, standard deviation; CL, 90% confidence limits; AU, arbitrary units.

Qualitative Inferences *(QI)*: Trivial *(T)*; Small *(S)*; Moderate *(M)*; Large, *(L)*.

*25-75%, possibly; **75-95%, likely; ***95-99.5%, very likely.

4.4.6 Individual changes in markers of neuromuscular function

Individual participant data for relative PPO and JH are presented in Figures 16A and 16B. For relative PPO, the range of individual percentage changes from baseline at 0h, +2h, and +24h were -11 – 4%, -3 – 9%, and -7 – 4%, respectively (Figure 16A). For JH, the range of individual percentage changes from baseline at 0h, +2h, and +24h were -16 – 1%, -8 – 8%, and -23 – 5%, respectively (Figure 16B).

4.4.7 Individual changes in biochemical markers

Figures 16C and 16D present the individual participant data for BLa and CK concentrations. For CK, individual percentage increases from baseline at 0h, +2h, and +24h ranged from 22 – 179%, 18 – 208%, and -21 – 134%, respectively (Figure 16D). For BLa, the percentage changes at 0h, +2h, and 24h ranged from -21.5 – 377%, -63 – 11%, and -43 – 99%, respectively (Figure 16C).

4.4.8 Individual changes in mood questionnaires

Individual participant data for mood scores are presented in Figure 17A. The individual percentage changes in mood scores from baseline at 0h, +2h, and +24h ranged from -1 – 280%, -20 – 236%, and -46 – 120%, respectively (Figure 17A).

4.4.9 Individual changes in hormones

The individual participant data for T, C, and the T:C ratio are presented in Figures 17B, 17C, and 17D, respectively. Individual percentage changes in T concentration from baseline at 0h, +2h, and +24h ranged from -48 – 98%, -55 – 32%, and -60 – 182%, respectively (Figure 17B). For C concentrations, the individual percentage change values from baseline ranged from -76 – 163%, -86 – -27%, and -57 – 110% at 0h, +2h, and +24h, respectively (Figure 17C). For the T:C ratio, the individual percentage changes from baseline ranged from -59 – 217% at 0h, from -32 – 310% at +2h, and from -22 – 158% at 24h (Figure 17D).

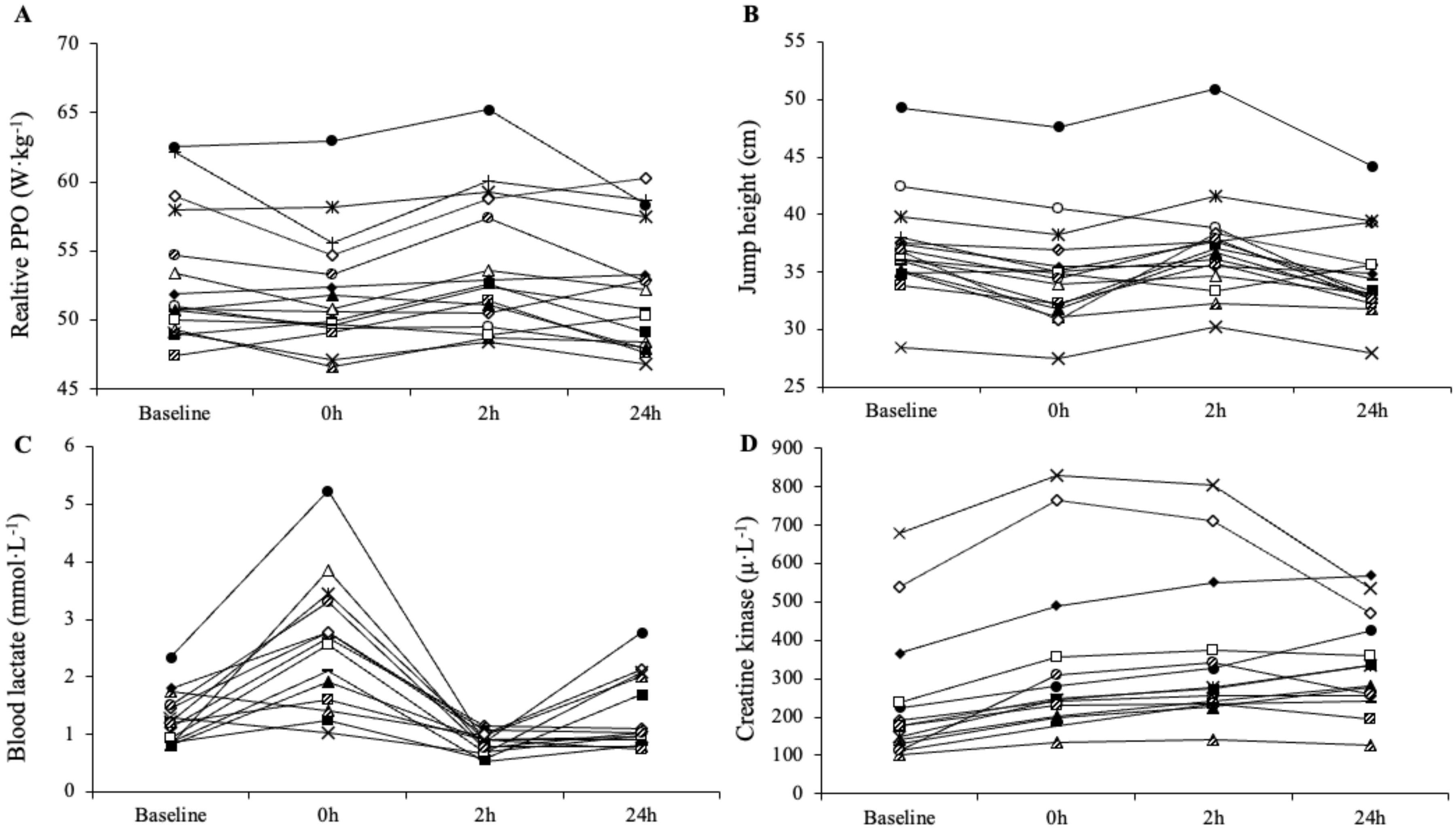

Figure 16 (A – D). Individual participant data for relative PPO (panel A), jump height (panel B), blood lactate (panel C) and creatine kinase (panel D) at pre (baseline) and post (0h, 2h and 24h) SSG training. Each symbol represents a different participant.

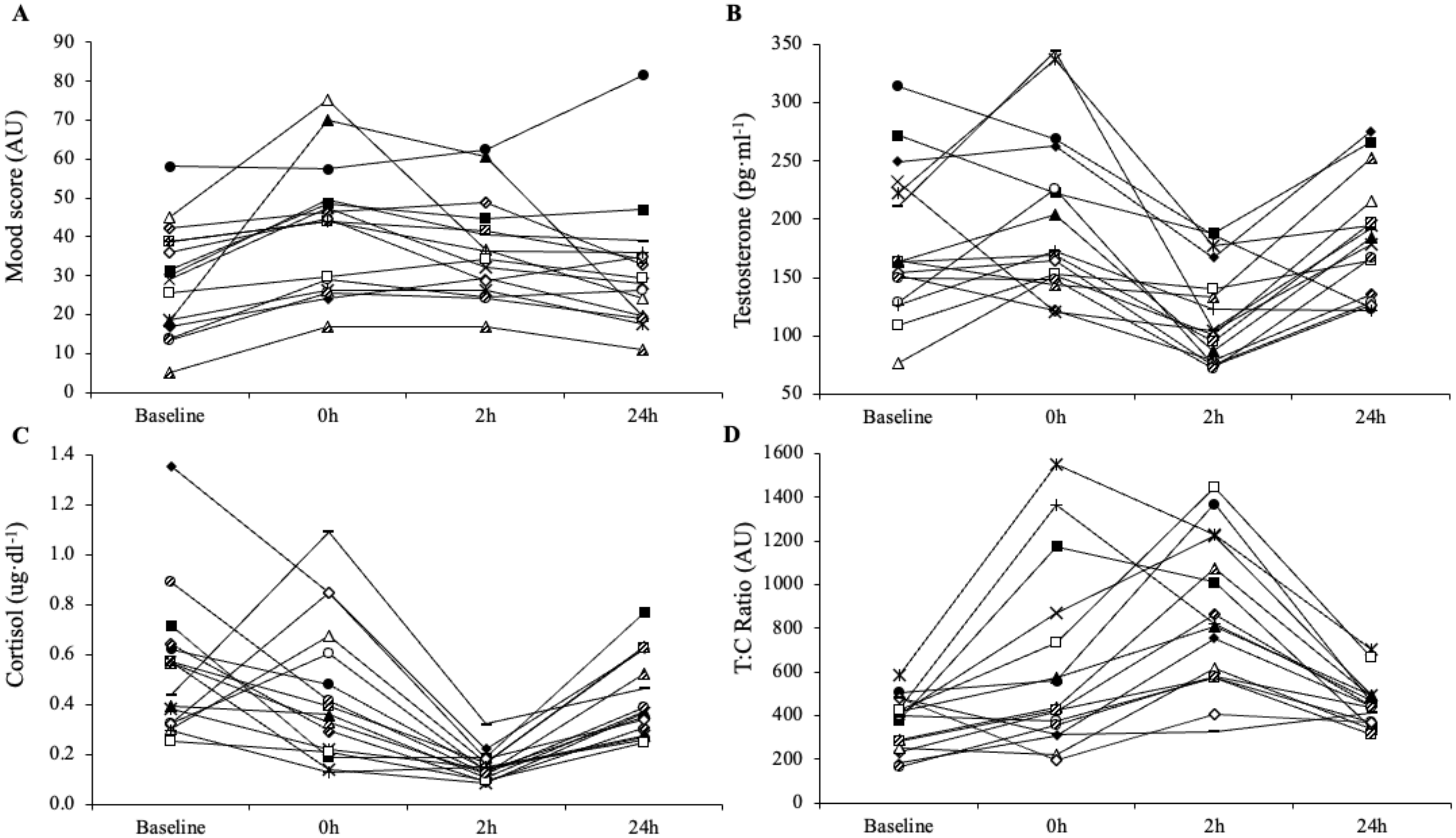

Figure 17 (A – D). Individual participant data for mood score (panel A), testosterone (panel B), cortisol (panel C), and the T:C ratio (panel D) at pre (baseline) and post (0h, 2h and 24h) SSG training. Each symbol represents a different participant.

4.5 DISCUSSION

The primary aim of this study was to characterise the neuromuscular, biochemical, endocrine and mood response of professional soccer players following an SSG training session. Immediate disturbances in mood, JH, relative PPO and CK occurred following 42-min of SSGs, which in the case of JH and relative PPO had returned to pre-exercise values following a 2-hour passive recovery period. On the following morning (+24h), there was a secondary impairment in CMJ performance (relative PPO & JH), whilst disturbances in CK persisted but mood scores had returned to baseline values. To our knowledge, this is the first study to profile the responses to SSG training over 24 hours; findings that will be of interest to those responsible for designing and monitoring soccer-specific training, especially given the possible influence that such acute changes may have on subsequent training design and recovery strategies used throughout the training week.

The SSG format was designed alongside the team coaching staff (UEFA pro-licence holders) to both replicate the workload players are exposed to during a typical training session, and also in accordance with previous SSG research (Hulka, Weisser, & Belka, 2016; Beenham et al., 2017; Lacome et al., 2018; Moran et al., 2019). The mean total distance covered per minute ($m \cdot min^{-1}$) over the six SSG repetitions was 104 ± 5 $m \cdot min^{-1}$, which for the SSG format selected (i.e., 4 vs 4 +GKs) was broadly similar to playing intensities reported in professional players by Lacome et al. (2018) (~105 $m \cdot min^{-1}$), but higher than reported in amateur players (~93 – 101 $m \cdot min^{-1}$) (Hodgson, Akenhead, & Thomas, 2014; Hulka, Weisser, & Belka, 2016; Casamichana, Bradley, & Castellano, 2018). These demands resulted in the players subjectively rating the session as 'very hard' (RPE; 7.1 ± 1.3 AU). In assessing the changes in external demands between SSG repetitions, the first repetition (SSG1) consistently produced the highest value for each metric, after which there was generally a gradual decline in playing intensity, with *moderate – large* reductions in SSG repetitions 2 – 6 in comparison to SSG1 (Table 10). This supports prior literature in this area that has reported declines in external load variables across SSG repetitions (Dellal et al., 2011b; Dellal, Drust, & Lago-Penas, 2012; Clemente et al., 2017; Clemente et al., 2019b; Clemente et al., 2020; Bujalance-Moreno et al., 2020; Younesi et al., 2021). It is suggested that if the aim was to maintain the playing intensity across repetitions, then increasing the between-repetition rest periods may alleviate these declines (Ade, Harley, & Bradley, 2014). However, given that the physical demands in competitive 11 vs 11 match-play also follow a gradual decline across halves, with the first 15-

min period of each half consistently producing higher physical outputs than the last 15-min period (Bradley et al., 2009; Carling & Dupont, 2011; Russell et al., 2014; Barrett et al., 2016), it could be suggested that keeping the rest periods to a minimum is more specific to the demands of actual match-play.

Although a *likely large* increase in BLa immediately after completion of the SSGs was observed (Table 10), the magnitude of the increases observed here are low in comparison to other SSG studies (Coutts et al., 2009; Köklü et al., 2011). This difference occurred despite pitch size and game rules being similar (i.e., 4 vs 4 +GKs), however, it is hard to compare the external load of the present study to the previous studies mentioned, as they occurred before the introduction of GPS technology. This could be a result of differences in session volume and intensity, player training status or skill level as we present data from professional in-season soccer players who are likely to be more accustomed to this type of training. Notably, the previous studies mentioned here recruited younger elite players (<16 yr) and recreational athletes (Coutts et al., 2009; Köklü et al., 2011). Furthermore, it is well known that BLa concentrations in soccer are highly influenced by the activity of the player in the preceding 5-min period before sampling (Bangsbo et al., 1991; Krustrup et al., 2006), and considering we saw a gradual decline in playing intensity here, this could go some way in explaining the results.

The initial impairment in CMJ performance in the current study agrees with previous soccer literature, which has reported immediate declines in JH after matches (-12%; Magalhães et al., 2010) and simulation protocols (-12%; Thomas et al., 2017). However, the reductions in JH at 0h in the present study (-8.6 ± 12.4%) appear to be of a lower magnitude than 90-min of activity (Magalhães et al., 2010; Thomas et al., 2017), but greater than a 12 – 24-min position specific soccer training drill conducted with a similar cohort of soccer players (-4%; Ade et al., 2021). This may highlight that a greater volume of soccer activity has more of a detrimental impact on markers of neuromuscular function; SSG playing volume was 42-min vs match-play (≥90-min). Although the precise mechanisms of neuromuscular fatigue were not elucidated in the present study, previous literature in this area is unanimous in finding that match-related fatigue is determined by a combination of central and peripheral mechanisms (Rampinini et al., 2011; Goodall et al., 2017; Thomas et al., 2017; Brownstein et al., 2017). Goodall et al. (2017) obtained neuromuscular measurements throughout the time course of a 120-min match simulation protocol, reporting that significant central and peripheral fatigue manifests as early as half time (i.e., 45-min), before a progressive decline thereafter. Therefore, it is possible that processes originating at the spinal or supraspinal level may have contributed to the immediate declines in JH and relative PPO found in the current study. Peripheral mechanisms that may have contributed to the initial impairment in CMJ performance at 0h may be attributed to a combination of metabolite accumulation (e.g., H^+, ADP, Pi) and energy substrate depletion (e.g., ATP, PCr, glycogen), resulting in a reduced functioning of the contractile properties of the muscle fibres (Binder-Macleod & Russ, 1999; Byrne et al., 2004; Allen, Lamb, & Westerblad, 2008; Johnston et al., 2015a). However, as the origins of fatigue (i.e., central vs peripheral) were not studied here, these mechanisms remain speculative and future work may be necessary to determine the aetiology of neuromuscular fatigue after SSG training.

Whilst relative PPO (*possibly small*; -2.1 ± 3.8%) and JH (*possibly moderate*; -8.6 ± 12.4%) were immediately impaired, these markers had returned to baseline values after 2 hours of passive recovery. Mood scores in the current study presented a similar pattern but were still higher than baseline values at +2h (*likely small*; +27.4 ± 76.8%%). This would suggest that if multiple sessions are programmed on the same day (e.g., on-field training and resistance training) as is often the case in professional soccer (Cross et al., 2019), then the 2 hours post time point may represent a window in which further training could be undertaken if effects of impaired neuromuscular function and mood wish to be ameliorated. Furthermore, the *likely large* reduction in C (-71.8 ± 17.7%) and increase in the T:C ratio (+130.4 ± 101.7%) +2h may be noteworthy here, given the potential moderating effect of C on T and the potential influence of this relationship on neuromuscular performance (Crewther et al., 2011b; Crewther et al., 2017). Despite the recovery of neuromuscular variables at +2h, there was a secondary impairment in PPO (*possibly small*; -1.7 ± 3.4%) and JH (*likely small*; -6.8 ± 6.3%) at +24h; perhaps suggesting that SSC derived neuromuscular fatigue follows a bimodal recovery pattern as described by previous authors (Dousset et al., 2007; Johnston et al., 2015a). Taking this timeframe into account, it is hypothesised that the recovery of relative PPO and JH observed at +2h occurred before the initiation of the inflammatory response and was most likely due to the removal of the metabolic by-products that had initially built up immediately after the SSGs (Dousset et al., 2007; Johnston et al., 2015a). The secondary decline in relative PPO and JH observed at +24h may be related to the inflammatory process which is likely to be in process at this time point (Johnston et al., 2015a). Previous studies examining the recovery time course of neuromuscular measurements after 90-min of soccer activity have reported that there is typically a slower recovery of peripheral fatigue indicators (Rampinini et al., 2011; Thomas et al., 2017), perhaps suggesting that the impairments at +24h were associated with processes distal of the NMJ, rather than processes within the CNS (Rampinini et al., 2011; Thomas et al., 2017). This is likely a consequence of the repetitive high-force eccentric and SSC activities during SSGs (e.g., accelerations, decelerations, changing direction, kicking, tackling, and body contact), which are known to have the potential of inducing muscle damage and impair neuromuscular function 24 hours later (de Hoyo et al., 2016; Hader et al., 2019). This is supported by the elevated CK concentrations at +24h (*very likely small*; +39.2 ± 51.6%) in the present study, indicating that muscle damage was present.

The declines in PPO and JH at +24h may also have implications for training design. The current study supports previous research which has shown that jump and sprint performance are impaired in the presence of muscle damage and soreness induced by training 24 hours prior (Highton, Twist, & Eston, 2009). Given this, it may be advised to place explosive or maximal effort training relatively close together, and practitioners may consider programming their training in a manner that takes advantage of maintained neuromuscular performance. However, as there is limited data on the impact of performing multiple same-day training sessions in soccer players, further research is required to examine the effect of performing multiple daily training on muscle damage, neuromuscular performance, and changes in perceived fatigue and hormones. It is also suggested that performance in submaximal activities would appear to be less affected at +24h. Therefore, a strategy of alternating high-intensity explosive training days containing multiple sessions with training days emphasising submaximal technical or tactical activities may take advantage of the observed pattern of neuromuscular performance.

At a group level, immediately after the SSGs, there were *possibly small* increases and decreases in T (+11.1 ± 39.7%) and C (-16.5 ± 81.4%), respectively, which resulted in a *possibly moderate* increase in the T:C ratio at 0h (+66.6 ± 81.4%). Whilst this is the first study to report the hormonal responses to the format of SSG training investigated here, the mean changes we observed at 0h were similar to those reported after speed training (Johnston et al., 2015a) and strength training (McCaulley et al., 2009), but lower than those reported post hypertrophy training (McCaulley et al., 2009). As previous work has highlighted that metabolic accumulation is linked to post-exercise elevations of T (Lu et al., 1997; Walker, Ahtiainen, & Hakkinen, 2010) and C (Spiering et al., 2008a), it may be that the comparable lower BLa concentrations immediately post the training protocol in the current study may partly explain this. However, when examining the individual changes in hormones in the current study

(Figure 17), there was considerable inter-individual variability in the responses, and large individual changes may have been masked when interpreting the data at a group level. This agrees with previous literature, which has reported highly individual hormonal changes in response to exercise (Jensen et al., 1991; Beaven, Gill, & Cook, 2008; Gaviglio et al., 2015). Whilst T and C were both found to be reduced from baseline values when measured at +2h (*likely moderate – large effects*), the T:C ratio was well above baseline values (*likely large*; +130.4 ± 101.7%). The time course of declines in T and C at +2h are unsurprising, as this aligns with the normal circadian declines previously reported in the literature (Kraemer et al., 2001), where T and C in men have been shown to peak in the early morning followed by progressive reduction thereafter (McLellan, 2010). Therefore, it seems unlikely that these declines were a direct response to the training stimulus. However, it is possible that the concentrations of T and C were significantly altered from normal values at that time of day, although, the lack of non-exercise control data in the current study means that this cannot be confirmed.

On the following day (+24h), the T:C ratio was still above baseline values (*likely large*; +22.2 ± 54.2%), which was mostly driven by a reduction in C (*likely small*; -21.3 ± 40.9%). This decline in C at +24h post SSG is an interesting finding and could have been related to an anticipatory rise in C at baseline prior to undertaking the SSG training. Many studies in a wide range of sports have reported that C concentrations are higher on a competition day before the start of the warm-up relative to the same time of day on a neutral non-competition day (Passelergue & Lac, 1999; Gonzalez-Bono et al., 1999; Suay et al., 1999; Salvador et al., 2003; Alix-Sy, Le Scanff, & Filaire. 2008; Filaire et al., 2009). This is thought to reflect a psychophysiological mechanism influenced by cognitive anticipation and anxiety; used by some athletes as an arousal and coping mechanism to manage pre-competition stress (Papacosta, Nassis, & Gleeson, 2016). Although we were not assessing actual competitive match play here, it is possible that SSG training may evoke a similar response. Indeed, the players were informed of the training protocol before taking part in the study, therefore, they knew that they were going to be competing against each other in a physically demanding and competitive training session.

4.5.1 Applied implications

As presented in Figures 16 and 17, there was considerable inter-individual variability in the responses to the SSG training session, which may have implications for practitioners working in applied settings. As discussed above, the changes in hormones were particularly variable, with one participant experiencing an increase in T of 98% at 0h, whilst another experienced a decline of 48% at the same time point (Figure 17B). Similarly, from baseline to 0h, individual percentage changes in C and the T:C ratio ranged from -76 – 163% and -59 – 217%, respectively (Figure 17C and Figure 17D). This supports previous authors who have reported that there are highly individual changes in hormones in response to exercise, which may vary in both the direction and magnitude of change (Jensen et al., 1991; Beaven, Gill, & Cook, 2008; Gaviglio et al., 2015). Numerous factors such as training status (Ahtiainen et al., 2004), baseline strength (Crewther et al., 2012), genetics (Crewther et al., 2009a), and nutrition (Hackney, Smith-Ryan, & Fink, 2020) are thought to potentially modulate this response. Furthermore, changes in hormone concentrations may not only be driven by the physical stimulus, but also psychological (Suay et al., 1999; Cook & Crewther, 2012a), social (Archer, 2006), and motivational factors (Cook, Crewther, & Kilduff, 2013). Therefore, it is possible that various factors highlighted above may have influenced the inter-individual responses. Nonetheless, to our knowledge, this is the first study to report the endocrine responses to SSG training in professional players, and our data support previous literature suggesting that strenuous exercise may drive large individual changes in hormone concentrations which may be masked when analysing data at a group level (Beaven, Gill, & Cook, 2008; Gaviglio et al., 2015). Furthermore, practitioners would be advised to recognise that individual players may respond very differently to the same training session or protocol.

There were also considerable individual differences in the magnitude of change in CMJ variables and CK. For example, in comparison to baseline values, the range of individual percentage changes in relative PPO at 0h, +2h, and +24h ranged from -11 – 4%, -3 – 9%, and -7 – 4%, respectively (Figure 16A). Similarly, whilst there were consistent group mean increases in CK concentrations at each time point relative to baseline, individual percentage changes at 0h, +2h, and +24h ranged from 22 – 179%, 18 – 208%, and -21 – 134%, respectively (Figure 16D). Individual differences in markers of neuromuscular performance and muscle damage have previously been reported after soccer matches (de Hoyo et al., 2016; Brownstein et al., 2017), which may be influenced by the physical performance characteristics of the players (Johnston et al., 2015b; Owen et al., 2015). Johnston et al. (2015b) reported lower post-match CK concentrations and less pronounced declines in CMJ performance in rugby league players with better-developed high-intensity running ability and lower body strength, as assessed by Yo-Yo intermittent recovery test and 3RM squat performance, respectively. These differences occurred despite the players with better developed physical qualities producing higher internal and external match loads (Johnston et al., 2015b). Similarly, in professional soccer players, Owen et al. (2015) reported negative correlations (*moderate – very large)* between lower body strength and incidences of muscle damage at 48 hours post matches; assessed by 4RM half-squat and CK concentrations, respectively. Therefore, it is possible that differences in the physical qualities of the players in this study may have influenced the degree of fatigue experienced. Whilst exploring these relationships went beyond the scope of the current study, future work should establish the influence of physical performance characteristics on the magnitude of fatigue experienced after training exercises in soccer players. Furthermore, this reinforces the importance and may provide further rationale for developing lower body strength in soccer.

Another important consideration is that since SSGs are fundamentally a dynamic interaction between two teams under various contextual factors, the demands are inherently unpredictable and uncontrolled (Clemente, 2019a). Indeed, previous investigations have revealed that there is a considerable degree of inter-individual variability in the movement demands during both 11 vs 11 matches (Rampinini et al., 2007b; Gregson et al., 2010) and SSG of various formats (Clemente, 2019a; Clemente et al., 2021). Importantly, the variables most associated with fatigue in soccer (i.e., high-intensity running distance and the number of accelerations and decelerations) are typically the most variable metrics (Gregson et al., 2010; Ade, Harley, & Bradley, 2014; Clemente et al., 2019b; Milanović et al., 2020; Younesi et al., 2021). Considering that previous research has reported significant relationships between these match activities and post-match incidences of muscle damage and declines in neuromuscular function (Russell et al., 2016b; de Hoyo et al., 2016; Hader et al., 2019), it is unsurprising that the magnitude of fatigue and in turn, the time-course of recovery, can be highly variable between subjects (de Hoyo et al., 2016; Brownstein et al., 2017). In practice, the factors discussed above reinforce the importance of monitoring both the activity profiles and the consequential responses of athletes. Furthermore, the individual data presented in this study may give practitioners insight into the range of individual responses expected from a comprehensive battery of tests.

4.5.2 Limitations

There are several limitations that should be considered when interpreting the results of this study, which were generally due to the applied nature of this research. Firstly, due to alignment with the club monitoring strategy at the time of the study, no markers of internal load (i.e., HR) or acceleration and deceleration metrics were available for export during the SSGs. Whilst the training load metrics reported (i.e., RPE, total distance, HSR, and PlayerLoad^{TM}) are widely used in previous soccer literature (e.g., Ade, Harley, & Bradley, 2014; Barrett, Midgley, & Lovell, 2014; Russell et al., 2016b; Beenham et al., 2017; Owen et al., 2017b; Rowell et al., 2018) and prevalent in applied settings (Akenhead & Nassis, 2016), the capture of additional metrics may have given a more comprehensive picture of the physical demands during SSG training. On a similar topic, whilst the HSR threshold applied in this study (i.e., $\geq$19.8 km.h^{-1}) is very common in previous literature (e.g., Thorpe & Sunderland, 2012; Gaudino et al., 2013; Lacome et al., 2018) and reported at professional clubs (Akenhead & Nassis, 2016), it is acknowledged that for the pitch size used it is relatively high, which is likely to have inhibited the ability of players to fully accelerate to the required velocity to register as a high-intensity effort. This is highlighted by the mean HSR distance being only 41 ± 30 m over the SSGs (Table 10). Therefore, the capture of running distances at lower speed thresholds may have given a more comprehensive picture of the physical demands during the SSGs and been more appropriate for the pitch size used (width x length; 24 x 29 m). It is also well known that varying the pitch size and player numbers can alter the physical demands of SSGs (Hodgson et al., 2014; Lacome et al., 2018). Therefore, it is acknowledged that the results of this study may be specific to the SSG format chosen (i.e., 4 vs 4 +GKs), and future work should investigate the responses to other SSG formats with varying pitch sizes and player numbers.

Another limitation that is important to recognise is that due to the logistical constraints of obtaining a comprehensive battery of measurements from a squad of players immediately after a training session, there were inevitably slight differences in the proximity of each assessment to the cessation of exercise. Therefore, it is possible that each measurement did not capture the full extent of neuromuscular fatigue before it dissipated (Taylor & Gandevia, 2008). It is acknowledged that this may have contributed to the individual variability presented in this study. However, individual differences in fatigue responses have previously been highlighted after soccer matches (de Hoyo et al., 2016; Brownstein et al., 2017), and Brownstein et al. (2017) obtained measurements between 10 – 60 minutes post-match and reported no relationships between the proximity of the assessment to the end of the match and the magnitude of neuromuscular fatigue experienced. A similar limitation may pertain to the proximity of the CMJ test to the cessation of the pre-jump warm-up (Tsurubami et al., 2020). Furthermore, it is also acknowledged that the on-field warm-up prior to the SSGs was relatively short, consisting of 5-min of mobility exercises, dynamic stretching, and short sprints, and it is possible that this did not elicit all the potential temperature and non-temperature related mechanisms of warm-up (Bishop, 2003). However, the highest values for the training load markers (i.e., total distance, HSR, and PlayerLoad™) were observed during the first SSG repetition, with *moderate – large* reductions thereafter, which might suggest that the short warm-up did not have a considerable detrimental effect on SSG performance.

Further limitations pertain to nutrition and hydration, and whilst food and water were provided at the training facility and participants were instructed to follow their normal dietary routines, there was no strict control of nutrition and hydration status in the days prior to and during the study. It is recognised that differences in individual nutrition and hydration may have had an impact on the physical output during training and the subsequent physiological responses (Oliveira et al., 2017). Furthermore, despite SSG training being undertaken in a subjectively temperate environment, there was no specific measurement of this to report, which is a limitation. In addition, it may have been useful to continue the measurements beyond 24 hours to establish a complete time course of recovery for all measurements. Finally, in an attempt to control the baseline condition of the players, two rest days were given prior to undertaking the study. For many teams, this may not follow their typical microcycle structure and they may wish to schedule SSG training on the day after a previous high-intensity training session. Therefore, practitioners would be advised to consider this when interpreting the results of this study and where they schedule SSG training throughout the week, how this may influence the physical demands, the physiological responses, and the impact this may have on the performance of additional training sessions.

4.6 CONCLUSIONS AND PRACTICAL APPLICATIONS

In summary, this study revealed that SSG training induced immediate fatigue as evidenced by *small – moderate* disturbances in CMJ performance, mood and CK, which in the case of CMJ variables had returned to pre-exercise values following a 2-hour passive recovery period. On the following morning, there was a secondary impairment in CMJ performance, whilst disturbances in CK persisted but mood scores had returned to near baseline values. In addition, there were large individual changes in concentrations of T and C over the 24-hour period. There are several practical applications that can be taken from this study which may be of interest to those responsible for monitoring and designing soccer training programs:

- As soccer players are often required to concurrently train multiple physical qualities on the same day (i.e., strength and soccer), it is suggested that physically demanding sessions should be spaced with an adequate recovery period (≥2 hours) between sessions.
- The 24-hour fatigue response to SSGs should be taken into consideration when designing a microcycle in soccer.
- It is suggested that performance in submaximal activities would appear to be unaffected at 24 hours post. Therefore, a strategy of alternating high-intensity explosive training days containing multiple sessions with days emphasising submaximal technical/ tactical activities may be beneficial.
- It is advised that those responsible for the design of soccer training programs should allow adequate recovery time (>24 hours) between SSGs and competitive matches.
- For the SSG format chosen here, the intensity of the movement demands during repetitions seems to follow a pattern of a gradual decline, whereby the first repetition is of significantly higher intensity than the following repetitions. This may be favourable if looking to target aerobic adaptations, however a strategy of allowing longer rest periods (i.e., ≥2-min) may maintain the intensity across repetitions, likely inducing more of an anaerobic training stimulus.
- The individual data presented in this study highlights that there may be considerable inter-individual variability in the responses to SSG training and provides practitioners with a potential range of values that may be expected.

Chapter 5.

The Neuromuscular, Endocrine and Mood Responses to a Single Versus Double Training Session Day in Soccer Players

5.1 INTRODUCTION

Due to the multifaceted match requirements in soccer, concurrent training methods are typically implemented to simultaneously target the multiple physical qualities aligned to successful performance (Bangsbo, 1994a; Stølen et al., 2005; Morgans et al., 2014; Cross et al., 2019). Whilst players must have well developed aerobic capacities (Stølen et al., 2005), the key match demands that are often decisive in determining the outcome of a game (e.g., accelerating, sprinting, changing direction, kicking, jumping, tackling) are underpinned by the ability to exert a large amount of force in a short timeframe (i.e., power) (Stølen et al., 2005; Faude, Koch, & Meyer, 2012). Maximal strength is a fundamental quality that influences power performance, as an increase in maximal strength is often associated with an improvement in relative strength to bodyweight ratio, and therefore improved ability to express power (Moss et al., 1997; Baker & Nance, 1999; Baker, 2001; Baker, 2002; Stone et al., 2003). Indeed, significant relationships have been reported between maximal strength and KPIs in soccer, such as acceleration ability ($r = 0.94$), maximal speed ($r = 0.71$), COD ability ($r = 0.68$), JH ($r = 0.78$) (Wisloff et al., 2004), as well as heading ($r = 0.80$) and tackling success ($r = 0.61$) (Wing, Turner, & Bishop, 2018). Furthermore, greater strength may accelerate the post-match recovery rate (Owen et al., 2015) and reduce injury rates (Lehnhart et al., 1996; McCall et al., 2014; Opar et al., 2015), which is related to a higher league placing over a season in soccer (Hagglund et al., 2013; Carling et al., 2015). Therefore, it is unsurprising that resistance training is often an integral component in a soccer training program (Turner & Stewart, 2014; Silva, Nassis, & Rebelo, 2015).

Due to the high fixture demands in elite soccer (e.g., ~40 – 50 fixtures over ~10 – 11 months) and that there is often limited training time between fixtures (e.g., 3 – 7 days), this leaves restricted training time to develop physical qualities (Morgans et al., 2014). Therefore, both high-intensity field-based and resistance training sessions are often undertaken on the same day and within 24 hours of each other (Hoff & Helgerud, 2004; McCall et al., 2014; Enright et al., 2015; Cross et al., 2019). However, there is evidence that the simultaneous integration of resistance and aerobic exercise into a training program (i.e., concurrent training) compromises the development of strength and power in comparison to undertaking resistance training alone (Hickson, 1980; Leveritt et al., 1999; Wilson et al., 2012; Fyfe, Bishop, & Stepto, 2014). Whilst these interference mechanisms are likely multifactorial, research indicates that the endurance exercise interferes with the ability to perform the resistance training session (via residual fatigue and/ or substrate depletion), as well as moderations in the acute molecular responses that mediate strength and power adaptation (Leveritt et al., 1999; Baar, 2006; Hawley, 2009). Moreover, if athletes are in a sub-optimal condition (e.g., impaired neuromuscular function, increased muscle damage, diminished energy stores, mental fatigue), then they may be less able to perform the high-intensity explosive movements required to recruit the high threshold motor units necessary for inducing the neural adaptations associated with strength, power and speed (Tan, 1999). Therefore, it is recommended that training sessions aimed at targeting these neuromuscular adaptations are sequenced or spaced in a logical timeframe that allows the athletes to recover to a point where they can undertake training in a sufficient condition (Bishop, Jones, & Woods, 2008).

Chapter 4 has revealed that whilst there may be an impairment of neuromuscular function immediately after an SSG training session in soccer, there may be a temporary recovery at 2 hours post, before a secondary decline on the following day. Evidence of this bimodal recovery pattern has also been reported post speed training (Johnston et al., 2015a), marathon running (Avela, et al., 1999), AFL (Cormack, Newton, & McGuigan, 2008) and soccer matches (Andersson et al., 2008). Therefore, it seems that the performance of a second training session at 2 hours post may not be dampened. However, it is unclear whether the addition of a second training session may further impair neuromuscular performance and recovery status at 24 hours post. This is worthy of investigation, given that soccer players often train on consecutive days, and indeed, on the day following a double training session (Malone et al., 2015a; Enright et al., 2015; Martín-García et al., 2018b; Cross et al., 2019). A better understanding of these responses would allow coaches to make informed decisions on the use of twice-daily training. More specifically, decisions on the placement, sequence, and the volume and intensity of training sessions they may wish to have the athlete perform during the rest of the training week.

The majority of research looking at the responses to multiple daily training sessions has examined the combined effects of similar training modalities (e.g., resistance training twice daily) (Hakkinen, 1992; Hakkinen & Pakarinen, 1993), or a combination of conventional endurance training (e.g., steady-state or interval running or cycling) and resistance training (Coffey et al., 2009a; Wilson et al., 2012; Doma et al., 2019; Lee et al., 2020). However, it is not well understood how neuromuscular performance is affected in the 24 hours following the double session, and whether this differs according to the number of sessions performed. Whilst multiple daily resistance training sessions are often undertaken by weightlifters (Hartman et al., 2007) and endurance athletes (Doma & Deakin, 2013), team sport players are often required to combine resistance training with on-field training (e.g., SSGs) which may have varying demands (Enright et al., 2015; Jones et al., 2016a; Cross et al., 2019). Johnston et al. (2016) compared the 24-hour responses from a single speed training session to a double session (i.e., speed followed by weights) training day in elite rugby players. Their data indicate that the addition of a weight training session aimed at the development of strength 2 hours after a speed session did not influence endocrine responses or neuromuscular performance at 24 hours post, despite the participants reporting a higher perception of muscle soreness. However, the acute response to combined resistance and on-field training in soccer is currently unclear.

Intense dynamic exercises containing repeated eccentric or SSC actions are likely to result in muscle damage, inflammation, perceived fatigue, muscle soreness, and reduced neuromuscular performance in the hours and days that follow (Dousset et al., 2007; Burt et al., 2014; Johnston et al., 2016). In addition, these modes of exercise may induce changes in the concentrations of the hormones T (Hakkinen & Pakarinen, 1993) and C (Cormack, Newton, & McGuigan, 2008), which could influence both acute neuromuscular performance and chronic adaptations to training (Ahtiainen et al., 2003). It has been suggested that variation in exercise stimuli is a factor that may exacerbate these responses (Coffey et al., 2009b). Therefore, it is important to consider the combined effect of two training sessions performed within proximity to each other, to determine what impact this has on indicators of fatigue and neuromuscular performance in the 24 hours following a double training day.

To date, no studies have reported the fatigue and recovery profiles of combined SSG and resistance training sessions on the same day. This is somewhat surprising given the prevalence of such practises in applied scenarios. This information would allow coaches to make informed decisions on where to structure double training session days throughout the week, and the impact this may have on the performance of the subsequent day of training. Therefore, this study aims to compare the 24-hour neuromuscular, endocrine and mood response from a single training session day consisting of SSGs, vs a double training session day consisting of SSG and resistance training 2 hours later in soccer players.

5.2 METHODS

5.2.1 Experimental design

Each experimental protocol was completed over two days on consecutive weeks. The study took place midway through the 2017-18 competitive season with players being given 72 hours of rest before test involvement. CMJ performance (relative PPO and JH), saliva (T and C concentrations), and brief assessment of mood (BAM+) responses were collected before (pre), and after (immediately post, 0h; 24 hours post, 24h) SSG training. The following week, players returned and completed the same protocol, with the inclusion of a lower-body resistance training session aimed at the development of strength 2 hours after completion the SSG session. On week 2, the 0h time point remained immediately post the completion of the SSGs.

5.2.2 Participants

Data are presented from 12 male semi-professional soccer players (age, 21 ± 2 yr; mass, 80.1 ± 6.8 kg; height, 1.81 ± 0.06 m). Despite the involvement of GKs in the SSG protocol, only data from outfield players were included in the analyses. All players were considered healthy and injury-free at the time of the study. Ethical approval was granted by the ethics advisory board of Swansea University and the players were informed of the risks and benefits and provided written informed consent prior to participation (Appendix 1 – 3). Players were in the maintenance phase of their training season, and on a typical microcycle which consisted of 1 game·week^{-1}, players were completing two on-field training sessions (~60 – 90-min) and one resistance training session (~1-hour).

5.2.3 Procedures

On arrival at the training centre (17:00 h), pre salivary samples, BAM+ mood questionnaire scores and CMJ performance were assessed. Prior to CMJ testing, players completed a 5-min standardized warm-up consisting of jogging and dynamic stretching. The SSG training session began at 17:30 h. Follow up measures (saliva, BAM+, CMJs) were collected at 0h and 24h post-training. The following week, the procedure was repeated, but with the addition of a lower body strength training session 2 hours after the completion of the SSGs (20:30 h). Immediately after the 0h data collection during both trials, players were provided with water, a banana, and a recovery bar (Lucozade elite; energy, 171 kcal; fats, 3.7 g; carbohydrate, 20 g; sugars, 9.3 g; protein, 14 g) and were instructed to consume only this in the 2 hours between training sessions.

5.2.3.1 Small-sided games

The SSG format was standardised as described in chapter 3.3.1.

5.2.3.2 Resistance training session

The content of the lower-body resistance training session is detailed in chapter 3.3.2.

5.2.3.3 Time-motion analysis

Movement demands of the SSGs were recorded using 10 Hz GPS devices (OptimEye S5, Catapult Innovations, Melbourne, Australia). Metrics exported for analyses in this study were total distance, HSR and Playerload^{TM}, which aligned with the normal club monitoring strategy and have been studied extensively in previous literature. Please refer to chapter 3.4.1 for a detailed description of the time-motion analyses methods in this study.

5.2.3.4 Rating of perceived exertion

Subjective markers of training load were obtained for each training session using the methods outlined in chapter 3.4.2.

5.2.3.5 Neuromuscular function

A portable FP (Type 92866AA, Kistler Instruments Ltd., Farnborough, United Kingdom) was used to measure neuromuscular performance of the lower body. Measures taken from the CMJ were relative PPO ($W \cdot kg^{-1}$) and JH (cm). For more detail, please refer to chapter 3.5.

5.2.3.6 Hormonal response

Salivary T and C concentrations were collected as per the methods outlined in chapter 3.6.

5.2.3.7 Mood assessment

Mood state was assessed using a modified version of the brief assessment of mood questionnaire (BAM+; Appendix 4). Please refer to chapter 3.7 for more detail.

5.3 STATISTICAL ANALYSIS

Data are reported as mean ± SD. Visual inspection of the residual plots revealed no clear evidence of heteroscedasticity, so all analyses were performed on the raw untransformed data. Custom-made spreadsheets were used to analyse the effect of training session (single, double) on our neuromuscular, endocrine, and mood markers (Hopkins, 2006). The analysis of within training session effects was made using the post-only crossover spreadsheet, with the analysis of between-group changes (single training session vs double training session) made using the before and after parallel-group spreadsheet. Here, we used the pre value of the dependent variable as a covariate to control for pre imbalances between the single and double training sessions. The uncertainty of our estimates is expressed as 90% confidence limits (CL). Standardised thresholds for small, moderate, and large effects derived from between-player standard deviations of the pre values (0.2, 0.6 and 1.2, respectively) were used to assess the magnitude of all effects and probability of the effect was interpreted using the following scale: 25–75%, possibly; 75–95%, likely; 95–99.5%, very likely; >99.5%, most likely (Batterham & Hopkins, 2006). We classified the magnitude of effects mechanistically, whereby if the 90% CL overlapped the thresholds for the smallest worthwhile positive and negative effects, the effect was deemed unclear (Hopkins et al., 2009). A paired T-test was applied to determine if there were any significant differences in the measured physical demands (GPS metrics and RPE) of the SSG training during both trials.

5.4 RESULTS

5.4.1 Physical demands of small-sided games

Analyses revealed that there were no significant differences between the physical demands during the SSGs on week 1 (single) vs week 2 (double). Values for RPE (single, 7.3 ± 0.8; double, 7.7 ± 0.7), total distance (single, 4475 ± 397 m; double, 4315 ± 641 m), HSR (single, 21 ± 22 m; double, 30 ± 35 m), and Playerload™ (single, 452 ± 59 AU; double, 444 ± 85 AU) were all similar between trials ($p > 0.05$).

5.4.2 Neuromuscular function

Mean data for the changes in JH and relative PPO between each time point are presented in Table 12. Between-trial comparisons (single vs double) revealed that there was a greater reduction in JH following the double training session, both between time points pre – 24h, and 0h – 24h (*possibly small*) (Table 12). Within-trial analyses revealed predominantly *small* changes in JH between time points for both the single and double sessions (Table 12). A *likely small* impairment in relative PPO was observed after the double session compared to the single session between time points pre – 24h, and 0h – 24h (Table 12). Within-trial analyses for the single and double sessions revealed predominantly *small* effects across time points (Table 12).

5.4.3 Mood questionnaires

Mean data for the changes in mood scores between each time point are presented in Table 12. Between-trial comparisons (single vs double) revealed that the double session resulted in a greater disturbance in mood score (*possibly small*), both between pre – 24h, and 0h – 24h (Table 12). Within-trial analyses revealed that at 0h after the SSG training during both trials there were *likely moderate* disturbances in mood compared to pre (Table 12). Furthermore, during the single trial, there was a *very likely moderate* improvement in mood score between time points 0h – 24h, whereas there was a *possibly moderate* improvement between the same time points (0h – 24h) during the double session trial (Table 12).

Table 12. Group mean (± SD) data for changes in mood and neuromuscular variables between time points. Qualitative inferences are shown for both the within and between-trial differences (single vs double session).

		Comparison		
Variable	Trial	Pre – 0h	Pre – 24h	0h – 24h
Mood score (AU)	Single ± SD	+9.8 ± 11.2 (*Moderate***)	-2.1 ± 7.7 (*Trivial**)	-11.9 ± 14.6 (*Moderate****)
	Double ± SD	+10.4 ± 7.2 (*Moderate***)	+2.5 ± 6.8 (*Trivial**)	-7.9 ± 8.8 (*Moderate**)
	Between trial difference ± 90% CL	0.6 ± 7.5 (*Trivial**)	4.6 ± 6.1 (*Small**)	4.0 ± 7.3 (*Small**)
JH (cm)	Single ± SD	-1.6 ± 2.7 (*Small**)	+0.5 ± 2.7 (*Trivial***)	+2.1 ± 2.5 (*Small***)
	Double ± SD	-1.7 ± 3.8 (*Small***)	-0.8 ± 1.9 (*Small**)	+0.9 ± 3.9 (*Small**)
	Between trial difference ± 90% CL	-0.1 ± 1.3 (*Trivial***)	-1.3 ± 2.0 (*Small**)	-1.2 ± 2.1 (*Small**)
Relative PPO ($W \cdot Kg^{-1}$)	Single ± SD	-0.3 ± 3.6 (*Trivial**)	+1.0 ± 3.9 (*Small**)	+1.2 ± 3.9 (*Small**)
	Double ± SD	-0.9 ± 3.3 (*Small**)	-1.5 ± 1.9 (*Small**)	-0.6 ± 3.9 (*Trivial**)
	Between trial difference ± 90% CL	-0.6 ± 1.5 (*Trivial**)	-2.5 ± 2.2 (*Small***)	-1.8 ± 2.2 (*Small***)

Abbreviations: SD, standard deviation; SSG, small-sided game; AU, arbitrary units.

Magnitude-based inferences: *25-75%, *possibly*; **75-95%, *likely*; ***95-99.5%, *very likely*.

5.4.4 Hormonal response

Mean data for the between time point changes in T, C, and the T:C are presented in Table 13. Between-trial comparisons (single vs double) revealed greater reductions in T (*likely small*) following the double compared to the single training session, between time points pre – 24h, and 0h –24h (Table 13). Within-trial analyses revealed no notable changes in T following the single session (*likely – very likely trivial*), however, after the double session there were *possibly small* decreases between pre – 24h, and 0h – 24h. For C, within-trial analyses revealed that there were *possibly small* decreases between each time point following the single session, whereas there were no notable changes across time points during the double session trial (*possibly – very likely trivial*) (Table 13). This resulted in *likely small* between-trial differences in the changes in C between pre – 24h, and 0h – 24h (Table 13). For the T:C ratio, there were *possibly – likely small* increases immediately after SSG training sessions during both trials (Table 13). Furthermore, within-trial analyses revealed *possibly small* increases and decreases between pre – 24h during the single and double trials, respectively (Table 13). This resulted in *very likely small* between-trial differences for the pre – 24h changes in T:C (Table 13).

Table 13. Group mean (± SD) endocrine marker changes between time points. Qualitative inferences are shown for both the within and between-trial differences (single vs double session).

		Comparison		
Variable	Trial	Pre – 0h	Pre – 24h	0h – 24h
Testosterone (pg·ml^{-1})	Single ± SD	+3.6 ± 26.3 (*Trivial***)	-0.8 ± 61.7 (*Trivial****)	-4.4 ± 65.5 (*Trivial***)
	Double ± SD	+3.0 ± 27.9 (*Trivial***)	-16.0 ± 54.8 (*Small**)	-19.0 ± 59.9 (*Small**)
	Between trial difference ± 90% CL	-0.6 ± 5.7 (*Trivial****)	-15.2 ± 6.1 (*Small***)	-14.6 ± 6.2 (*Small***)
Cortisol (ug·dl^{-1})	Single ± SD	-0.035 ± 0.251 (*Small**)	-0.078 ± 0.152 (*Small**)	-0.043 ± 0.240 (*Small**)
	Double ± SD	-0.022 ± 0.234 (*Trivial**)	-0.006 ± 0.143 (*Trivial****)	+0.016 ± 0.244 (*Trivial***)
	Between trial difference ± 90% CL	0.013 ± 0.020 (*Trivial****)	0.072 ± 0.034 (*Small***)	0.059 ± 0.045 (*Small***)
T:C ratio (AU)	Single ± SD	+138.3 ± 336.8 (*Small***)	+53.6 ± 93.9 (*Small**)	-84.8 ± 294.2 (*Small**)
	Double ± SD	+74.0 ± 190.2 (*Small**)	-43.0 ± 69.5 (*Small**)	-117.0 ± 194.4 (*Small***)
	Between trial difference ± 90% CL	-64.3 ± 85.0 (*Small**)	-96.6 ± 36.7 (*Small****)	-32.3 ± 71.3 (*Trivial**)

SD, standard deviation; SSG, small-sided game; AU, arbitrary units.

Magnitude-based inferences: *25-75%, *possibly*; **75-95%, *likely*; ***95-99.5%, *very likely*.

5.4.5 Individual changes in neuromuscular function

Individual participant and group mean data for JH and relative PPO are presented in Figures 18 C – F. During the single training session trial, the individual percentage changes in JH between time points pre – 0h, pre – 24h, and 0h – 24h ranged from -19 – 10%, -6 – 17%, and -3 – 34%, respectively (Figure 18C). During the double training session trial, the individual percentage changes in JH between the same time points ranged from -35 – 12% (pre – 0h), -14 – 6% (pre – 24h), and -16 – 34% (0h – 24h) (Figure 18D). For relative PPO, individual percentage changes during the single training session trial between time points pre – 0h, pre – 24h, and 0h – 24h ranged from -14 – 10%, -14 – 13%, and -11 – 18%, respectively (Figure 18E). During the double training session trial, the percentage changes in relative PPO ranged from -17 – 4% (pre – 0h), -9 – 6% (pre – 24h), and -12 – 15% (0h – 24h) (Figure 18F).

5.4.6 Individual changes in mood questionnaires

Individual participant and group mean data for mood scores during the single and double trials are presented in Figure 18A and Figure 18B, respectively. During the single training session trial, the individual percentage changes in mood score between time points pre – 0h, pre – 24h, and 0h – 24h ranged from -15 – 252%, -56 – 28%, and -82 – 23%, respectively (Figure 18A). During the double training session trial, the individual percentage changes between the same time points ranged from 5 – 92% (pre – 0h), -25 – 60% (pre – 24h), and -48 – 18% (0h – 24h) (Figure 18B).

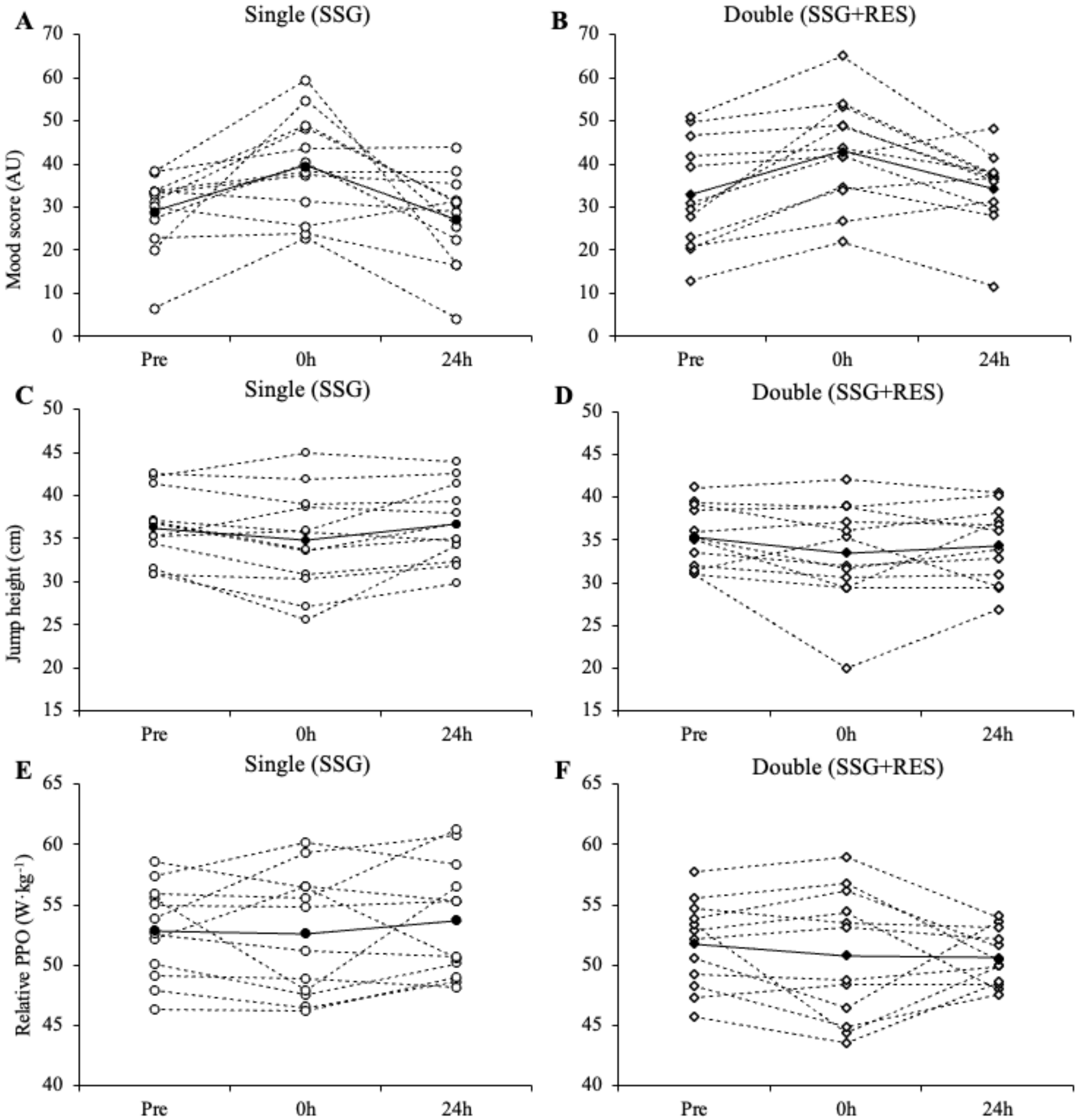

Figure 18 (A – F). Individual participant (hollow markers with dashed lines) and group mean data (full markers with solid lines) at each time point for mood score (panel A & B), JH (panel C & D), and relative PPO (panel E & F) responses to single and double training session days.

5.4.7 Individual changes in hormones

Individual participant and group mean data for T, C, and the T:C ratio are presented in Figure 19. During the single training session trial, individual percentage changes in T concentration between time points pre – 0h, pre – 24h, and 0h – 24h ranged from -20 – 36%, -61 – 83%, and -54 – 76%, respectively (Figure 19A). During the double training session trial, the percentage changes in T between the same time points ranged from -20 – 38% (pre – 0h), -67 – 58% (pre – 24h), and -59 – 52% (0h – 24h) (Figure 19B). For C concentrations during the single training session trial, the individual percentage changes between pre – 0h, pre – 24h, and 0h – 24h ranged from -57 – 163%, -57 – 110%, and -60 – 105%, respectively (Figure 19C). During the double training session trial, the individual percentage changes in C between the same time points ranged from -51 – 147% (pre – 0h), -53 – 61% (pre – 24h), and -56 – 98% (0h – 24h) (Figure 19D). For the T:C ratio, individual percentage changes during the single training session trial ranged from -59 – 217%, -22 – 87%, and -66 – 91% between time points pre – 0h, pre – 24h, and 0h – 24h, respectively (Figure 19E). During the double training session trial, individual percentage changes for the T:C ratio ranged from -54 – 107% (pre – 0h), -44 – 75% (pre – 24h), and -70 – 71% (0h – 24h) (Figure 19F).

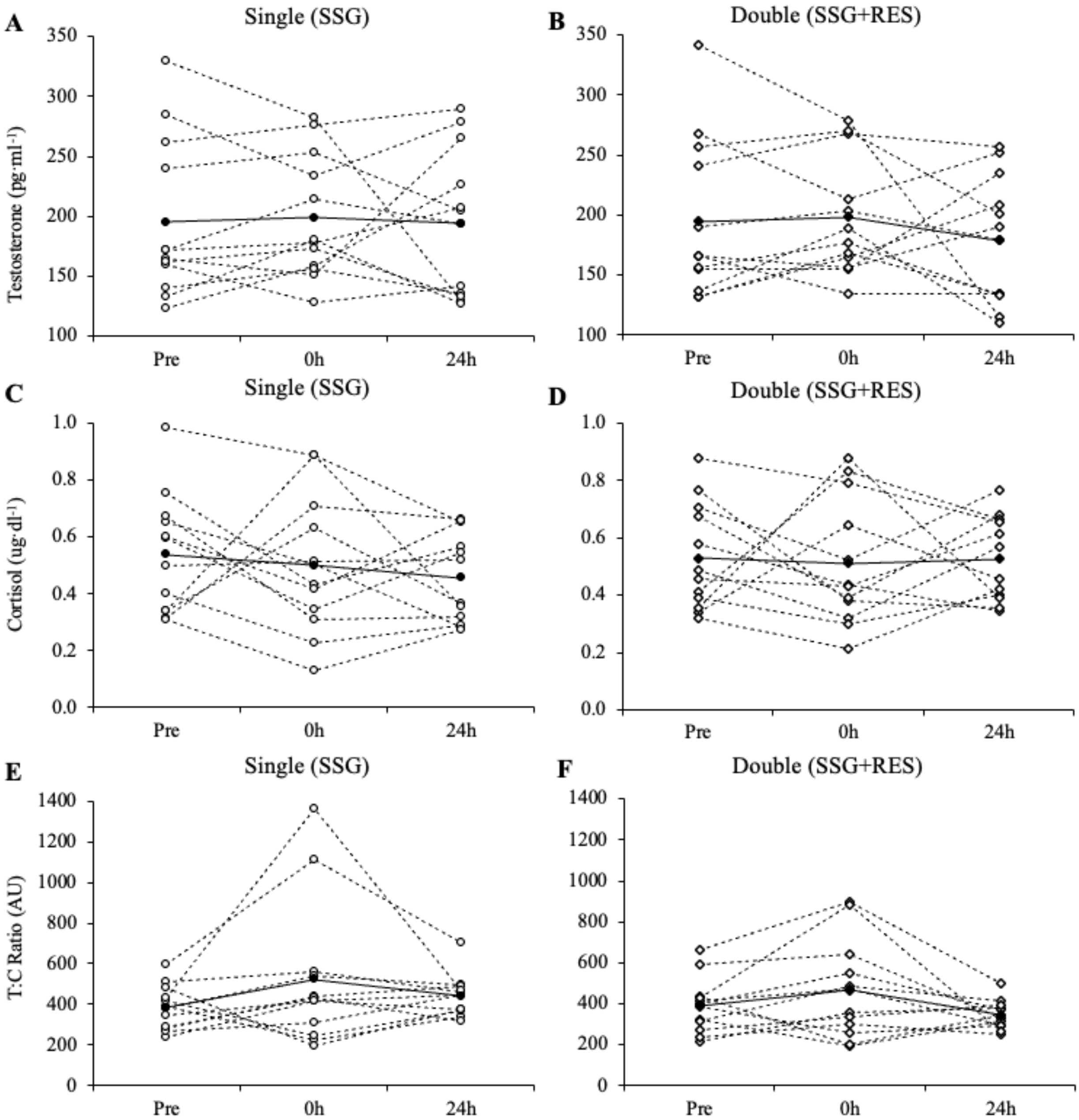

Figure 19 (A – F). Individual participant (hollow markers with dashed lines) and group mean data (full markers with solid lines) at each time point for testosterone (panel A & B), cortisol (panel C & D), and the T:C ratio (panel E & F) responses to single and double training session days.

5.5 DISCUSSION

The aim of this study was to compare the 24-hour responses of neuromuscular, endocrine and mood markers following a single session training day consisting of SSGs, to a double training session day consisting of SSGs and a resistance training session performed 2 hours later. On both trials, the SSG training (6 x 7-min; 42-min total playing time) induced immediate fatigue as evidenced by *small* decreases in JH (single, -1.6 ± 2.7 cm; double, -1.7 ± 3.8 cm) and *moderate* disturbances in mood (single, +9.8 ± 11.2 AU; double, +10.4 ± 7.2 AU). Between-trial comparisons (single vs double) revealed that the addition of a lower body strength training session 2 hours after the SSGs resulted in further *small* impairments in neuromuscular function (relative PPO, -2.5 ± 2.2 $W \cdot Kg^{-1}$; JH, -1.3 ± 2.0 cm), mood (+4.6 ± 6.1 AU), and endocrine markers (T, -15.2 ± 6.1 $pg \cdot ml^{-1}$; C, +0.072 ± 0.034 $ug \cdot dl^{-1}$; T:C, -96.6 ± 36.7 AU) at 24 hours post, indicating additive fatigue effects.

It is unsurprising that immediately after the SSGs on both trials, there were *likely moderate* disturbances in mood score combined with *possibly* to *likely small* impairments in neuromuscular performance, results that agree with the findings from chapter 4 in response to the same SSG protocol in professional players. Although the precise mechanisms were not studied here, previous literature examining the neuromuscular response after real and simulated soccer matches suggests that a combination of central and peripheral mechanisms contribute to the post-match decrements in neuromuscular function (Rampinini et al., 2011; Goodall et al., 2017; Thomas et al., 2017; Brownstein et al., 2017). More specifically, explanations for the initial impairment in neuromuscular performance at 0h may include changes in action potentiation propagation, E-C coupling failure, impaired cross-bridge cycling, substrate depletion, and metabolite accumulation (Fitts, 1994; Binder-Macleod & Russ, 1999; Byrne et al., 2004; Allen, Lamb, & Westerblad, 2008; Johnston et al., 2015a). Furthermore, central mechanisms such as reduced excitatory output from the motor cortex, decreased responsiveness and excitability of the motor neurons, or increased inhibitory input due to peripheral feedback from type III and IV muscle afferents may have resulted in impaired motor drive (Taylor & Gandevia, 2008). It is likely that a combination of the mechanisms highlighted above may have contributed to the immediate declines in CMJ performance in the present study.

At a group level, the hormonal markers measured in the current study showed a similar pattern to both neuromuscular function and mood, with no between-trial differences in T and C immediately after SSG training. However, the addition of the weight training session resulted in lower concentrations of T (*likely small;* -15.2 ± 6.1 pg·ml^{-1}) and higher concentrations of C (*likely small*; +0.072 ± 0.034 ug·dl^{-1}) at 24 hours post (Table 13). These changes resulted in lower values for the T:C ratio at +24h after the double compared to the single training session day (*very likely small*; -96.6 ± 36.7 AU). Given the opposing roles of T and C in the regulation of protein metabolism, the T:C ratio is thought to reflect a balance of anabolic and catabolic activity, which may have implications for chronic adaptations, performance, and recovery (Busso et al., 1990; Kraemer et al., 2004; McLellan, Lovell, & Gass, 2010). Moreover, numerous studies have reported a link between an anabolic environment (i.e., increase in T with a reduction or maintenance in C) and acute improvements in explosive performance (Crewther et al., 2011b; Kraemer et al., 2004; Cook et al., 2014; Russell et al., 2016a). Several mechanisms have been proposed to influence these changes, such as cell signalling, cognitive function, motivation, and changes in concentrations of metabolites in skeletal muscle cells (Estrada et al., 2003; Crewther et al., 2011b; Crewther et al., 2016). In the current study, it is possible that the decreased T:C ratio following the double in comparison to the single session be reflective of the further impairments in neuromuscular performance and mood at 24 hours post (Kraemer & Ratamess, 2005).

The results of the current study are conflicting with previous studies that have assessed multiple daily resistance training (Nosaka & Newton, 2002), plyometric training (Skurvydas, Kamandulis, & Masiulis, 2010), and combined speed and resistance training (Johnston et al., 2016), which have reported that in comparison to a single training bout, neuromuscular function and markers of fatigue were not further impaired following two daily training sessions. A factor that may explain the differences between these findings and the current study is the training volume and modality. The studies mentioned above implemented shorter training protocols that were more anaerobic in energy demands, similar in contraction type and explosive in nature (e.g., sprints, strength training, plyometrics). By comparison, the SSG training in the current study accumulated a mean total distance of 4315 – 4475 m, was rated as 'very hard' on the RPE scale and was relatively long in total playing time (i.e., 42-min). Therefore, although HR markers were not collected here, it is plausible to suggest that the SSG training would have provided a potent aerobic stimulus. Previous literature has suggested that the simultaneous integration of resistance and conventional endurance exercise into a training program compromises the development of strength and power in comparison to undertaking resistance training alone (Hickson, 1980; Leveritt et al., 1999; Wilson et al., 2012; Fyfe, Bishop, & Stepto, 2014). Therefore, training volume may be a factor that exacerbates the interference effect in a concurrent training program (Wilson et al., 2012; Fyfe, Bishop, & Stepto, 2014). Furthermore, diverse contractile activity is a factor that may exacerbate the interference effect (Coffey et al., 2009b). This has important implications for training design, and practitioners should consider and attempt to mitigate the factors that may intensify the interference effect. Training order and between-session recovery time are also aspects that are thought to alter these responses (Wilson et al., 2012; Doma et al., 2019). In the current study, we considered the between-session recovery time by identifying the bimodal recovery pattern in response to the same SSG protocol in chapter 4 (i.e., providing 2 hours of between-session recovery time), which may explain why we found only *small* between-trial effects. It is possible to theorise that scheduling the SSG and resistance training sessions back-to-back may have resulted in further fatigue, although more research in this area is necessary. Finally, it remains to be seen if changing the order of SSG and resistance training alters the fatigue and recovery kinetics following a double training day in soccer, which will be addressed in chapter 6.

5.5.1 Applied implications

The individual participant data presented in Figures 18 and 19 demonstrates that there was considerable individual variability in the responses to training, which may have implications for practitioners working in applied settings. In agreement with chapter 4 and previous authors (Jensen et al., 1991; Beaven, Gill, & Cook, 2008; Gaviglio et al., 2015), the changes in hormones varied considerably between individuals (Figure 19). For example, individual percentage changes in T concentrations between time points pre – 24h ranged from -61 – 83% and -67 – 58% for the single and double trials, respectively. Large ranges of individual percentage changes were also evident between time points pre – 24h for C (single, -57 – 110%; double, -53 – 61%) and the T:C ratio (single, -22 – 87%; double, -44 – 75%). It is important to recognise that changes in hormones during the post-exercise recovery period are just part of a very complex signalling network that supports normal homeostatic function and assists in the responses and adaptations to external stimuli (Kraemer, Ratamess, & Nindl, 2017). Indeed, T and C have several functions in regulating anabolism (tissue growth and substrate restoration) and catabolism (tissue breakdown and metabolic regulation), but their responses depend upon interactions between multiple physiological mechanisms (Kraemer, Ratamess, & Nindl, 2017). It is thought that numerous intrinsic and extrinsic factors may influence the response of an individual, such as genetics (Crewther et al., 2009a), training history and baseline strength

(Ahtiainen et al., 2004; Crewther et al., 2012), and various psychological factors (Cook & Crewther, 2012a; Cook, Crewther, & Kilduff, 2013). Therefore, our data suggest that practitioners should be aware that large individual changes in T and C may be masked when interpreting data at a group level, and that hormones should be viewed in conjunction with other markers of performance and recovery.

There was also considerable individual variability in the markers of neuromuscular function and mood (Figure 18) For example, between time points pre – 24h in the current study, individual percentage changes in relative PPO ranged from -14 – 13% and -9 – 6% for the single and double trials, respectively. Similar individual differences were evident for JH (single, -6 – 17%; double, -14 – 6%), and mood scores (single, -56 – 28%; double, -25 – 60%). Substantial individual differences in fatigue responses have previously been reported following soccer matches (de Hoyo et al., 2016; Brownstein et al., 2017), which could be influenced by the physical performance characteristics of the players. Indeed, lower body strength (Owen et al., 2015) and high-intensity running ability (Johnston et al., 2015b) have been identified as important physical qualities to develop to minimise residual fatigue in the post-match recovery period. Players who possess greater eccentric strength may be more suited to deal with the high forces during the repetitive SSC activities known to induce fatigue and muscle damage (Byrne, Twist, & Eston, 2004; Miyaguchi & Demura, 2008). Whilst it went beyond the scope of the current study to explore these relationships, differences in the physical characteristics of the participants may have influenced the magnitude of fatigue experienced and further emphasises the importance of developing strength in soccer players.

Another important factor to consider during any game situation is that fundamentally it is a dynamic interaction between two teams under various constraints (e.g., technical, tactical, motivational, and situational), therefore, the demands are inherently random and uncontrolled (Carling et al., 2016; Clemente et al., 2021). Indeed, significant individual variability in the movement demands has been reported during both official matches (Carling et al., 2016; Oliva-Lozano et al., 2021) and SSGs (Clemente, 2019a; Clemente et al., 2021). Therefore, inter-individual differences in the physical demands may have influenced the degree of fatigue experienced. In practice, this reinforces the importance for practitioners to implement a monitoring strategy that can identify the dose (i.e., the training load) and the response (e.g., perceptual, neuromuscular, and metabolic) of each athlete and recognise that there may be notable differences between players. This may have implications for individual programming, and when an unusual individual response from a given physical stimulus is identified, those players may benefit from a modified training program in subsequent activities. Moreover, when an abnormally low or high fatigue response is observed, individual players may benefit from an increase or decrease in subsequent training load prescription, respectively. However, this should be highly dependent on the physical goals of the training session, and factors such as time in the microcycle (e.g., number of days pre- or post-match) and time in the season (e.g., pre-, mid-, or late-season) should be considered.

5.5.2 Limitations

It is acknowledged that there are several limitations in this study that should be considered when interpreting the results. Firstly, some teams may schedule a rest day following a double training session, therefore, the inclusion of additional time points beyond 24 hours post may have been beneficial to establish a full time course of recovery and investigate whether any fatigue effects persisted. In addition, whilst we attempted to control the baseline condition of the players by permitting 72 hours of rest before involvement in each trial, most teams (particularly professionals) are unlikely to afford this amount of rest prior to undertaking training during the season. It is possible that if players had trained or played in the days prior to undertaking training, this could alter the responses observed. Therefore, practitioners would be advised to consider where they schedule double training days in their environment and how this might relate to the results of this study.

Another limitation is that whilst the participants were instructed to follow their usual dietary routines in the days leading up to and during the study, there were no diet records kept or monitoring of hydration status. It is recognised that individual nutrition and hydration may impact both performance of training and the responses observed (Oliveira et al., 2017) Furthermore, whilst the SSG training sessions during both trials were subjectively performed under similar environmental conditions, the lack of a detailed recording of this is a limitation. It is also acknowledged that the collection of additional training load metrics during the SSGs (e.g., HR, accelerations, decelerations, and distances run at lower speed thresholds), and response markers (e.g., BLa, CK) may have given a more comprehensive understanding of the physical demands and the responses to the training sessions assessed in this study. Finally, an important consideration is that due to the logistical constraints of collecting multiple measurements from numerous players immediately after exercise, it is possible that the timing of each assessment to the cessation of exercise (training or warm-up) may have influenced the responses observed. Moreover, it is possible that if a participant had their assessments performed closer or further away from exercise cessation, this could have captured a greater or lower degree of neuromuscular fatigue, respectively.

5.6 CONCLUSIONS AND PRACTICAL APPLICATIONS

In summary, this study found that performance of a double training session day in soccer resulted in *possible – very likely small* impairments of neuromuscular performance, mood score and endocrine markers in comparison to a single training session at 24 hours post, suggesting that a lower body strength training session exacerbated the fatigue response. Likely explanations for this are that the additional mechanical and metabolic stress of the lower body resistance training resulted in further muscle damage, inflammation, metabolite accumulation, or decreased CNS function (Byrne et al., 2004; Taylor & Gandevia, 2008; Johnston et al., 2015a). To our knowledge, this is the first study to examine the acute response to combined SSG and resistance training in soccer players, and several findings may be of interest to those responsible for designing training programs:

- On-field training consisting of 42-min of SSGs combined with lower body strength training 2 hours later resulted in *small* disturbances in neuromuscular performance, mood, and endocrine markers over a 24-hour period in comparison to SSG training alone.
- The added 24-hour fatigue response from a double training session day should be considered when planning training programs, as players may require longer to recover before the next high-intensity training session.
- These findings suggest that a strategy of alternating high-intensity explosive training days containing multiple sessions with training days consisting of submaximal technical and tactical activities or recovery days may be beneficial.
- The individual data presented in this study suggests that there may be highly individual physiological and perceptual responses to soccer training and provides practitioners with a potential range of values to be expected.

Chapter 6.
The Effect of Training Order on Neuromuscular, Endocrine and Mood Response to Small-sided Games and Resistance Training Sessions Over a 24-Hour Period

6.1 INTRODUCTION

As limited training time often separates fixtures in soccer, the ability to simultaneously develop multiple physical, technical, and tactical qualities is pertinent to success (Bangsbo, 1994a; Stølen et al., 2005; Morgans et al., 2014; Lacome et al., 2018). Accordingly, concurrent training programs are often implemented in soccer, and multiple training sessions with differing targeted adaptations (e.g., strength and aerobic capacity) are often undertaken on the same day and in proximity to each other (Hoff & Helgerud, 2004; Enright et al., 2015; Cross et al., 2019). However, this training paradigm has been associated with an 'interference effect', whereby attenuated strength or aerobic adaptation may occur in comparison to those following isolated resistance or endurance training (Eddens, van Someren, & Howatson, 2018). This creates an important challenge for those responsible for designing concurrent training programs, and the variables that may attenuate the interference effect should be considered. A recent survey revealed that 92% of soccer teams scheduled resistance training following field-based training (Cross et al., 2019). However, the training order or sequence has been highlighted as a factor that may influence the acute responses and chronic adaptations to concurrent training (Fyfe, Bishop, & Stepto, 2014; Doma et al., 2019). Despite this, the research in this area is controversial and it seems that numerous variables may influence the order effect, such as the training volume, intensity, mode, frequency, as well as the training history of the athletes (Methenitis et al., 2018). With regards to these factors, there is a lack of research in team sports, and indeed, a better understanding of the variables that may attenuate the interference effect in soccer is warranted.

The majority of previous studies in this area have examined the effects of training order on chronic adaptations to various types of resistance training combined with traditional modes of endurance exercise, such as steady-state or interval running or cycling (Cadore et al., 2012b; Schumann et al., 2013; Doma et al., 2019). The research here can be interpreted depending on the training outcome the researchers have reported (e.g., endurance adaptations vs strength and power adaptations). With regards to endurance adaptations, some studies report that there are limited effects of training order (Collins & Snow, 1993; Wilson et al., 2012; Fyfe et al., 2016; Lee et al., 2020), whereas others suggest that resistance training before endurance training compromises endurance adaptations (Chtara et al., 2005; Doma, Deakin, & Bentley, 2017). On the other hand, some studies report that that resistance training prior to endurance training is favourable for strength and power adaptations (Wilson et al., 2012; Fyfe et al., 2016; Eddens, van Someren, & Howatson, 2018; Cadore et al., 2018), although not all are in agreement (Tarasi et al., 2011; Lee et al., 2020; Enright et al., 2015). Typically, these results are suggested to be a result of changes in the ability to perform training optimally, whereby the first exercise bout diminishes the performance of the second training bout via residual fatigue and substrate depletion, thus reducing adaptations to the second training modality (Doma, Deakin, & Bentley, 2017). However, other factors that may influence this are conflicting hormonal profiles (Bell et al., 2000; Schumann et al., 2013; Jones et al., 2017) and interferences in molecular signalling pathways, such as activation of AMP-activated protein kinase (AMPK) from endurance training impairing resistance training adaptation by inhibiting mechanistic target of rapamycin (mTOR) (Atherton et al., 2005; Spiering et al., 2008b).

Given the complex interactions between resistance and endurance training alluded to above, some studies have investigated the acute responses to training session order with the aim of better understanding the mechanisms that may be responsible for the interference effects. Doma and Deakin (2013) reported that resistance training prior to endurance running with 6 hours of inter-session recovery time resulted in reduced RE and muscle force generation capacity on the following day, whereas running before resistance training did not. Jones et al. (2017) reported that resistance training before endurance training was superior for performance during the resistance training session than vice versa, and this order resulted in favourable hormonal profiles, with reduced concentrations of C immediately and at 1-hour post-exercise. However, a similar study from the same author group reported that the anabolic signalling responses were not altered by manipulating the session order (Jones et al., 2016b). Furthermore, other studies have suggested that the sequence of training has a strong impact on the acute molecular responses (Coffey et al., 2009a; Coffey et al., 2009b). Whilst the studies above may give insight into the potential mechanisms of interference, given that most previous studies in this area have recruited recreationally active participants and implemented traditional protocols such as steady-state running or cycling, these results cannot necessarily be generalised to well-trained team sport athletes where the training demands are diverse.

Concerning the above, a limited number of studies have examined the chronic adaptations to differing training session orders in soccer players. McGawley and Andersson (2013) reported no between-group differences in several performance measures (i.e., 10m sprint, agility, RSA and aerobic capacity) when manipulating the order of interval and resistance training over a 5-week pre-season in 18 semi-professional players. However, in this study, the training sessions were performed back-to-back (i.e., with no between-session recovery time) and in addition to the players normal training programs, which may have influenced the results. Another study by Enright et al. (2015) studied the order effect of soccer and resistance training in 15 elite youth players over 5 weeks. The authors reported that whilst both groups improved markers of neuromuscular performance, the soccer prior to resistance training group outperformed their counterparts in most markers of strength and power after the 5-week training period. However, the between-session recovery time and nutrient intake differed between groups, with the resistance training first group only having ~30 – 45-min of recovery between sessions and consumed only a recovery shake in this period (~220 kcal: 25 g protein, 13 g carbohydrate, 0.5 g fat). In contrast, the soccer first group had 2 hours of recovery between sessions and consumed a nutrient-dense meal between training sessions. Considering that the between-session recovery time is likely a key factor that influences adaptations to concurrent training (Methenitis, 2018), this may go some way in explaining the findings.

Experimental chapter 4 in this thesis revealed that whilst there may be an impairment of neuromuscular function immediately after an SSG training session, there may be a temporary recovery 2 hours later, before a further impairment after 24 hours. This is consistent with the findings of Johnston et al. (2015a), who reported a temporary recovery of CMJ performance 2 hours after a speed training session in elite rugby players. Therefore, it seems that after 2 hours of passive recovery, the physical performance of a second intense neuromuscular training session may not be impaired. However, chapter 5 in this thesis also found that performance of a double training session (SSG followed by resistance training 2 hours later) resulted in further negative 24-hour disturbances in neuromuscular function, mood, and endocrine markers in comparison to a single training session. Whilst this is important for our understanding of the weekly planning of training, it is currently unclear whether changing the training session order would have any influence on the performance of the second session of the day or the impact this may have on additional training sessions throughout the week.

To date, no studies have examined the effects of manipulating the training session order on the acute neuromuscular, endocrine and mood responses in soccer. This represents an important gap in the literature and our practical understanding of how to best manipulate within-day planning. Given that multiple daily training sessions are often performed in soccer (Cross et al., 2019), a better understanding of this may assist training design. Therefore, this study aimed to investigate the effects of manipulating the order of SSG and resistance training on the performance of training, and the neuromuscular, endocrine and mood responses over 24 hours in soccer players.

6.2 METHODS

6.2.1 Experimental design

This study profiled two training days, one consisting of SSG training followed by resistance training 2 hours later (SSG+RES), and one consisting of resistance training followed by SSG training 2 hours later (RES+SSG). Each experimental protocol was completed over 24 hours on consecutive weeks. The study took place midway through the 2018-19 competitive season with players being given at least 72 hours of rest before involvement.

6.2.2 Participants

Data are presented from 14 male semi-professional soccer players (22 ± 3 years, mass: 79.3 ± 12.2 kg, height: 1.80 ± 0.08 m). All players were healthy, injury-free and in the maintenance phase of their season. On a typical microcycle, which consisted of 1 game·week^{-1}, players completed two on-field training sessions (~60 – 90-min) and one resistance training session (~1-hour). Ethical approval was granted by the ethics advisory board of Swansea University and the players were informed of the risks and benefits and provided written informed consent prior to participation (Appendix 1 – 3).

6.2.3 Procedures

Salivary hormone (T and C concentrations), CMJ performance (relative PPO and JH), and mood (BAM+ questionnaire) were collected before (pre), during (0h) and after (+24h) both protocols. In addition, saliva samples were also collected immediately prior to the second training session (+2h) during both protocols. On arrival at the training centre (17:00 h), pre-measures were collected (saliva, BAM+, and CMJs). The first training session began at 17:30 h, and immediately post-training (0h), CMJs, saliva, and BAM+, were repeated. After 2 hours of passive rest and immediately before the second training session (+2h), players repeated the saliva test, before undertaking the second training session, which began at 20:30 h. The following day (+24h; 17:00 h), players repeated all measures (saliva, BAM+ and CMJs). The following week, players repeated the procedure but with the training session order reversed. Immediately after the 0h testing during both protocols, players were provided with water, a banana, and a recovery bar (Lucozade elite; energy, 171 kcal; fats, 3.7 g; carbohydrate, 20 g; sugars, 9.3 g; protein, 14 g) and were instructed to consume only this during the 2-hour period before the next training session.

6.2.3.1 Small-sided games

The SSG format was standardised as described in chapter 3.3.1.

6.2.3.2 Resistance training session

The content of lower body resistance training session is detailed in chapter 3.3.2.

6.2.3.3 Time-motion analysis

Movement demands of the SSGs were recorded using 10 Hz GPS devices (OptimEye S5, Catapult Innovations, Melbourne, Australia). Metrics exported for analyses in this study were total distance, HSR and Playerload^{TM}, which aligned with the normal club monitoring strategy and have been studied extensively in previous literature. Please refer to chapter 3.4.1 for a detailed description of the time-motion analyses methods in this study.

6.2.3.4 Rating of perceived exertion

Subjective markers of training load were obtained using methods outlined in chapter 3.4.2.

6.2.3.5 Neuromuscular function

A portable FP (Type 92866AA, Kistler Instruments Ltd., Farnborough, United Kingdom) was used to measure neuromuscular performance of the lower body. Measures taken from the CMJ were relative PPO ($W \cdot kg^{-1}$) and JH (cm). For more detail, please refer to chapter 3.5.

6.2.3.6 Hormonal response

Salivary T and C concentrations were collected as per the methods outlined in chapter 3.6.

6.2.3.7 Mood assessment

Mood state was assessed using a modified version of the brief assessment of mood questionnaire (BAM+; Appendix 4). Please refer to chapter 3.7 for more detail.

6.3 STATISTICAL ANALYSES

Results are reported as mean ± SD. Data were collated using Microsoft Excel (Microsoft Corporation, US) where descriptive statistics and graphical interpretations were derived. Statistical analysis was carried out using a Statistical Package for the Social Sciences (version 19; SPSS Inc., Chicago, IL) with the significance level set at $p < 0.05$. Following screening of data for normality and homogeneity of variance, the effects of time and order of training were assessed using a two-way (time point and protocol) repeated measures analysis of variance test. Where significant F values for time or interaction between protocols were identified ($p < 0.05$), a post hoc pairwise comparison test with Bonferroni correction was applied to determine where the significant differences occurred. Effect sizes (ES), using Cohen's *d*, were calculated using a custom-made spreadsheet, with the following thresholds for interpretation: <0.2, *trivial;* 0.2 – 0.6, *small*; 0.6 – 1.2, *moderate*; 1.2 – 2, *large* (Hopkins, 2004). A paired T-test was applied to determine if there were any significant differences in the physical demands (GPS and RPE) of the training sessions between-trials.

6.4 RESULTS

6.4.1 Physical demands of small-sided games and resistance training

Physical metrics during the SSGs during both trials were similar for RPE (SSG+RES, 7.3 ± 1.0 AU; RES+SSG, 7.6 ± 1.1 AU), total distance (SSG+RES, 4659 ± 611 m; RES+SSG, 4660 ± 583 m), HSR (SSG+RES, 36 ± 28 m; RES+SSG, 35 ± 26 m), and Playerload^{TM} (SSG+RES, 470 ± 72 AU; RES+SSG, 465 ± 75 AU) ($p > 0.05$). However, RPE for the resistance training session was significantly higher for SSG+RES (7.5 ± 0.8 AU) than RES+SSG (6.6 ± 0.9 AU) ($p < 0.05$; *moderate*), although this did not result in a difference between weight lifted in the resistance training session, and each participant completed the sets and repetitions at the intensity prescribed (i.e., 85%1RM).

6.4.2 Neuromuscular function

Mean data for the changes in JH and relative PPO between time points are presented in Table 14. For JH, analyses revealed that there was a significant effect of time ($F = 10.986$; $p = 0.000$), whereby during RES+SSG, JH was significantly reduced at 0h before returning to near pre-values again at +24h (Table 14). During SSG+RES, JH remained similar to pre-values at all time points (Table 14). There were no significant interaction effects between protocols for JH ($F = 4.122$; $p = 0.052$), so no further analyses were conducted. For relative PPO, there was a significant effect of both time ($F = 5.877$; $p = 0.008$), and interaction between protocols ($F = 5.695$; $p = 0.009$). Further analyses revealed that during RES+SSG, relative PPO was significantly impaired at 0h before returning to near pre-values at +24h (Table 14). Relative PPO remained similar to pre-values during SSG+RES (Table 14). Post hoc analyses revealed that relative PPO was significantly impaired to a greater extent at 0h during RES+SSG in comparison to SSG+RES, however, there were no significant differences between protocols at +24h (Table 14).

6.4.3 Mood questionnaires

Mean data for the changes in mood score between time points are presented in Table 14. There was a significant time effect on mood score ($F = 4.117$, $p = 0.028$). During SSG+RES, mood score was significantly increased at 0h before returning to near pre-values at +24h (Table 14). Mood remained unchanged from pre-values during RES+SSG (Table 14). There was no interaction effect between protocols for mood score ($F = 1.460$; $p = 0.251$).

Table 14. Group mean (± SD) data for changes in mood and neuromuscular variables between time points. Data are shown for both the within and between protocol differences.

Variable		Pre – 0h	*d*	Pre – +24h	*d*
Mood Score (AU)	SSG+RES	8.6 ± 9.1 *	0.72 (M)	5.3 ± 11.1	0.44 (S)
	RES+SSG	3.2 ± 11.4	0.24 (S)	4.0 ± 8.5	0.29 (S)
	Protocol difference	-5.3 ± 11.2	0.52 (S)	-1.4 ± 14.8	0.14 (T)
JH (cm)	SSG+RES	-2.2 ± 3.1	0.4 (S)	-2.6 ± 4.9	0.49 (S)
	RES+SSG	-4.1 ± 2.6 *	0.67 (M)	-1.3 ± 2.0	0.25 (S)
	Protocol difference	-1.9 ± 3.3	0.68 (M)	1.2 ± 5.4	0.33 (S)
Relative PPO ($W \cdot kg^{-1}$)	SSG+RES	-0.84 ± 2.75	0.12 (T)	-1.95 ± 3.81	0.31 (S)
	RES+SSG	-3.53 ± 2.48 *	0.50 (S)	-1.56 ± 2.30	0.25 (S)
	Protocol difference	-2.69 ± 3.30 †	1.03 (M)	-0.37 ± 4.19	0.12 (T)

Abbreviations: SSG+RES, small-sided games followed by resistance training, RES+SSG, resistance training followed by small-sided games; SD, standard deviation; AU, arbitrary units; effect size, *d*; T, *trivial*; S, *small*; M, *moderate*.

* Indicates significant difference between time points (p <0.05).
† Indicates significant difference between protocols (p <0.05).

6.4.4 Hormonal response

Mean data for the changes in hormonal markers (within and between protocols) are presented in Table 15. Analyses revealed that there was a significant time effect on T (F = 5.471, p = 0.003), whereby during both protocols, T concentrations remained similar to pre-values at all time points with the exception of a significant reduction at +2h (Table 15). There was also a significant interaction effect for T (F = 5.196, p = 0.004), where further analyses revealed that there was a significantly greater elevation in T at 0h during RES+SSG in comparison to SSG+RES (Table 15). There was a significant effect of time on C (F = 11.665; p = 0.000), where similarly to T, during both protocols, C concentrations remained similar to pre-values at all time points with the exception of a significant reduction at +2h (Table 15). However, there was no interaction effect for C (F = 0.814; p = 0.494). There was also a significant effect of time on the T:C ratio (F = 15.333; p = 0.000). During RES+SSG, the T:C ratio was significantly elevated at 0h, and remained above baseline at +2h, before returning to pre-values at +24h (Table 15). During SSG+RES, the T:C ratio remained near to pre-values at all time points except for a significant increase at +2h (Table 15). However, there were no interaction effects between protocols for the T:C ratio (F = 0.877; p = 0.462).

Table 15. Group mean (± SD) data for changes in endocrine markers between time points. Data are shown for both the within and between protocol differences.

Variable		Pre – 0h	*d*	Pre – +2h	*d*	Pre – +24h	*d*
Testosterone ($pg\cdot ml^{-1}$)	SSG+RES	-4.4 ± 32.5	0.07 (T)	-48.0 ± 35.9*	0.89 (M)	-1.3 ± 71.8	0.02 (T)
	RES+SSG	17.0 ± 25.3	0.27 (S)	-33.2 ± 34.3*	0.59 (S)	-14.0 ± 62.0	0.24 (S)
	Protocol difference	21.4 ± 26.7 †	0.73 (M)	14.9 ± 27.6	0.42 (S)	-12.7 ± 32.4	0.19 (T)
Cortisol ($ug\cdot dl^{-1}$)	SSG+RES	-0.066 ± 0.279	0.30 (S)	-0.310 ± 0.192*	1.89 (L)	-0.065 ± 0.208	0.36 (S)
	RES+SSG	-0.057 ± 0.217	0.31 (S)	-0.251 ± 0.178*	1.72 (L)	-0.033 ± 0.173	0.21 (S)
	Protocol difference	0.009 ± 0.175	0.04 (T)	0.059 ± 0.100	0.32 (S)	0.032 ± 0.104	0.17 (T)
T:C ratio (AU)	SSG+RES	102.6 ± 216.9	0.52 (S)	322.1 ± 237.7*	1.73 (L)	35.7 ± 117.7	0.35 (S)
	RES+SSG	112.9 ± 115.0*	0.73 (M)	261.8 ± 232.4*	1.41 (L)	-11.0 ± 98.6	0.10 (T)
	Protocol difference	10.4 ± 170.5	0.06 (T)	-60.4 ± 212.8	0.26 (S)	-46.6 ± 109.2	0.43 (S)

Abbreviations: SSG+RES, small-sided games followed by resistance training, RES+SSG, resistance training followed by small-sided games; SD, standard deviation; AU, arbitrary units; effect size, *d*; T, *trivial*; S, *small*; M, *moderate*.

* Indicates significant difference between time points ($p < 0.05$).
† Indicates significant difference between protocols ($p < 0.05$).

6.4.5 Individual changes in neuromuscular function

Individual participant and group mean data for JH are presented in Figure 20C (SSG+RES) and Figure 20D (RES+SSG). During SSG+RES, the individual percentage changes in JH between time points pre – 0h ranged from -25 – 8%, and between pre – +24h ranged from -32 – 18% (Figure 20C). During RES+SSG, the percentage changes in JH between pre – 0h and pre – +24h ranged from -22 – 3% and -14 – 3%, respectively (Figure 20D). Individual participant and group mean data for relative PPO during both trials are presented in Figures 20 E and F. During SSG+RES, the individual percentage changes in relative PPO between time points pre – 0h ranged from -13 – 4%, and between and pre – +24h ranged from -12 – 13% (Figure 20E). During RES+SSG, the individual changes ranged from -13 – 0% and -10 – 3% between pre – 0h and pre – +24h, respectively (Figure 20F).

6.4.6 Individual changes in mood score

Individual participant and group mean data for mood scores are presented in Figures 20 A and B. During SSG+RES, individual percentage changes ranged from -27 – 179% between time points pre – 0h, and from -33 – 126% between time points pre – +24h (Figure 20A). During RES+SSG, the changes ranged from -21 – 293% and -12 – 267% between pre – 0h and pre – +24h, respectively (Figure 20B).

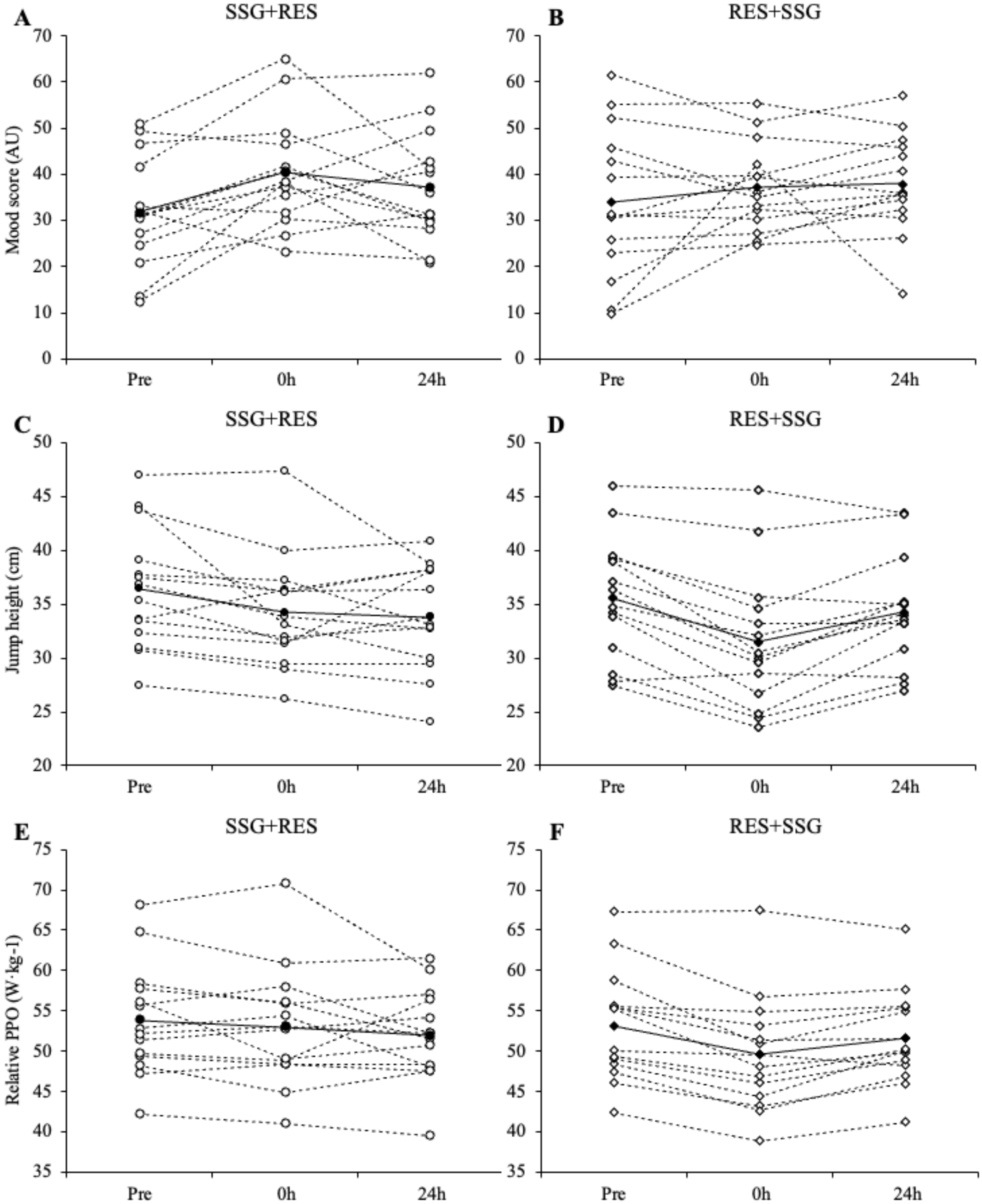

Figure 20 (A – F). Individual participant (hollow markers with dashed lines) and group mean data (full markers will solid lines) at each time point for mood score (panel A & B), JH (panel C & D), and relative PPO (panel E & F) responses to SSG+RES and RES+SSG training orders.

6.4.7 Individual changes in hormones

Individual participant and group mean data for T, C, and the T:C ratio are presented in Figures 21 A – F. For T concentrations during SSG+RES, the range of individual percentage changes from pre at 0h, +2h, and +24h were -20 – 38%, -36 – -6%, and -57 – 74%, respectively (Figure 21A). During RES+SSG, individual percentage changes in T between the same time points ranged from -20 – 28% (pre – 0h), -34 – 3% (pre – +2h), and -64 – 42% (pre – +24h) (Figure 21B). For C during SSG+RES, the range of individual percentage changes from pre at 0h, +2h, and +24h were -54 – 147%, -78 – -16%, and -57 – 110%, respectively (Figure 21C). During RES+SSG, individual percentage change values in C concentration ranged from -51 – 102% (pre – 0h), -74 – -19% (pre – +2h), and -53 – 61% (pre – +24h) (Figure 21D). For the T:C ratio, individual percentage changes during SSG+RES from pre at 0h, +2h, and +24h ranged from -54 – 107%, 1 – 286%, and -39 – 102%, respectively (Figure 21E). During RES+SSG, the individual range of percentage changes in the T:C ratio were -39 – 107% (pre – 0h), 5 – 215% (pre – +2h), and -39 – 88% (pre – +24h) (Figure 21F).

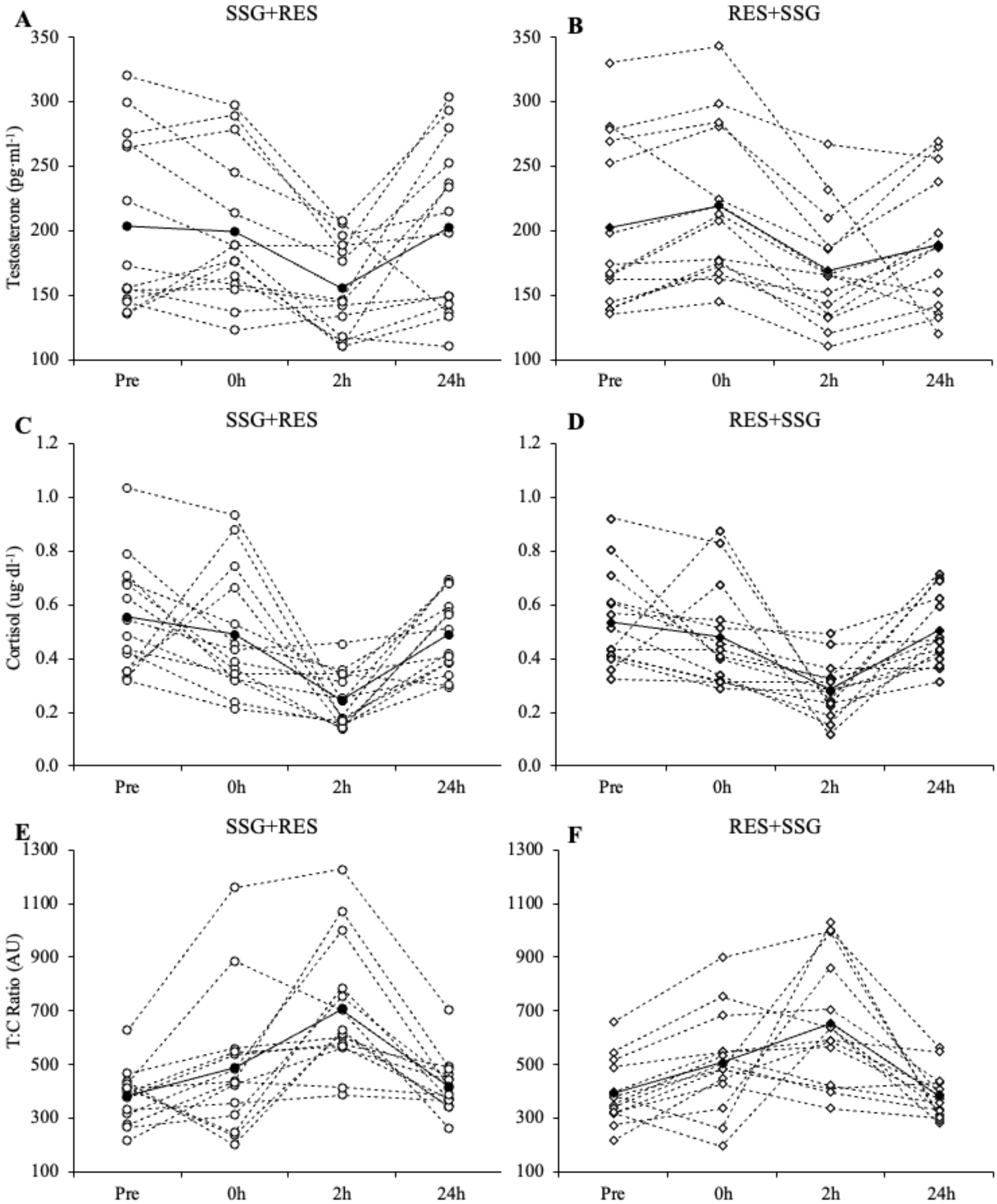

Figure 21 (A – F). Individual participant (hollow markers with dashed lines) and group mean data (full markers will solid lines) at each time point for T (panel A & B), C (panel C & D), and T:C ratio (panel E & F) responses to SSG+RES and RES+SSG training orders.

6.5 DISCUSSION

To our knowledge, this is the first study to examine the influence of manipulating the order of SSG and resistance training on acute neuromuscular, endocrine and mood responses over a 24-hour period. The primary study findings were that whilst comparison between the two training sequences revealed significant within-day differences in relative PPO and T concentration, by 24 hours post-training there were no significant differences between protocols, suggesting that the order of training does not influence the fatigue and recovery kinetics on the subsequent day (Table 14 & 15). In addition, the order of resistance and SSG training did not appear to influence the objective or subjective physical demands of SSG training, however, the RPE for the resistance training session was higher when performed 2 hours after SSG training, although this did not affect the prescribed weight lifted.

In the present study, the physical demands during SSG training (GPS metrics and RPE) were similar between trials, which suggests that the physical performance and intensity of SSG training may not be dampened when performed 2 hours after lower-body strength training. This supports previous work in academy rugby union players by Johnston et al. (2017), who reported that performance of a maximal speed training session (6 x 50 m maximal sprints with 5-min recovery) was maintained when undertaken 2 hours after a similar strength training session (i.e., 5 sets of 4 repetitions of the barbell back squat and the Romanian deadlift at 85% 1RM with 4-min recovery). Furthermore, the first 10 m split of the sprint times were enhanced (1.76 ± 0.08 s vs 1.80 ± 0.11 s) when performed 2 hours post resistance training (Johnston et al., 2017). Taking the results of this study along with the data presented here and in chapter 4, it seems likely that in well-trained athletes, the +2h time point represents a timeframe prior to the initiation of the inflammatory process but after metabolic recovery, during which the athlete can undertake additional intense training without performance being compromised.

In the current study, when resistance training was performed 2 hours after SSG training, the RPE for resistance training was higher (+0.9 ± 1.1 AU; $p < 0.05$; *moderate*), although this did not appear to affect the performance of the resistance training session, as each participant completed each set and repetition at the prescribed intensity (i.e., 4 sets of 4 repetitions at 85% 1RM of the barbell back squat, Romanian deadlift and hip thrust). This data supports Kraemer et al. (1995), who reported that in physically active men, the performance of resistance training was not compromised when undertaken ~5 – 6 hours after running-based endurance training.

However, our data somewhat contradict those of Jones et al. (2017), who reported that in recreationally trained men, the performance of strength training was compromised when undertaken immediately after endurance training (30-min treadmill running at 70% VO_{2max}). Here, the endurance training reduced the ability of participants to maintain the prescribed intensity (80% 1RM) of 5 sets of 6 repetitions of the back squat, bench press, bent over row, military press and deadlift interspersed by 2-min of recovery (Jones et al., 2017). Furthermore, Leveritt and Abernethy (1999), found that in recreationally trained participants, the number of isoinertial squats performed in 3 sets at 80% 1RM until failure was reduced when performed 30-min after 5 sets of 5-min bouts of high-intensity cycling. The discrepancy in findings between studies may be related to the recovery time given between training sessions, and it is likely that 30-min or less of rest may not be enough time to recover (e.g., reduce metabolite accumulation, replenish muscle glycogen stores, and restore neuromuscular function) from the prior training session. Indeed, from assessing previous literature it seems that when performing multiple daily training sessions, practitioners should separate training by ~2 – 6 hours to reduce residual fatigue, limit inhibition or potentially improve the performance of the second training session (Ekstrand et al., 2013; Fyfe, Bishop, & Stepto, 2014; Cook et al., 2014; Enright et al., 2015; Russell et al., 2016a; Johnston et al., 2017). It is possible to theorise that if athletes undertook a second daily training session in a sub-optimal condition, this would limit recruitment of high-threshold (i.e., type II) motor units and compromise force and power production (Sale, 1987; Tannerstedt, Apró, & Blomstrand, 2009). In turn, this may reduce the adaptations to strength training by inhibiting the phosphorylation of the enzymes p70S6K and mTOR, of which the response is more pronounced in type II than in type I muscle fibres (Parkington et al., 2003; Tannerstedt, Apró, & Blomstrand, 2009). Furthermore, the activation of various proteins by endurance-based training that are thought to inhibit protein synthesis (e.g., AMPK & eEF2K) and mediate protein degradation (e.g., MaFbx & MuRF-1) suggests that undertaking resistance exercise in very close proximity to endurance exercise may further compromise the anabolic response to resistance exercise (Thomson, Fick, & Gordon, 2008; Rose et al., 2009; Fyfe, Bishop, & Stepto, 2014). This is a possible explanation as to why previous studies report that adaptations to resistance exercise are reduced when undertaken after endurance exercise in comparison to vice versa (Eddens, van Someren, & Howatson, 2018; Murlasits, Kneffel, & Thalib, 2018), and compared to performing a resistance training alone (Hickson, 1980; Leveritt et al., 1999; Wilson et al., 2012; Fyfe, Bishop, & Stepto, 2014).

Comparisons between the two training sequences revealed that relative PPO was impaired to a greater extent immediately after the first training session during RES+SSG in comparison to SSG+RES (between trial difference; -2.69 ± 3.30 W·kg^{-1}; p <0.05; *moderate*). However, although JH decreased significantly at 0h during RES+SSG (-4.1 ± 2.6 cm; p <0.05; *moderate*), there were no significant interaction effects for JH (Table 14). The differing between trial interactions for JH and relative PPO may be related to a change in jump strategy, where previous authors have suggested that athletes may alter their mechanics to maximise the height of a CMJ under fatigue (Cormack, Newton, & McGuigan, 2008). Nevertheless, the additional declines in relative PPO immediately after the resistance training in comparison to SSG training could be explained by several reasons. Whilst neuromuscular fatigue is a complex phenomenon and various underpinning mechanisms may be responsible for a loss in force, and most likely, a combination (Abbiss & Laursen, 2005), the manifestation of neuromuscular fatigue is highly dependent on the type of muscle contraction and the characteristics of the musculature involved (Bosco, Luhtanen, & Komi, 1983; Collins et al., 2018). Due to the exercise selection of the resistance training session in the current study (particularly the back squat), it could be suggested that the targeted musculature shares a very similar movement pattern and muscle recruitment to a CMJ, therefore accumulating more task-dependent fatigue than the SSGs, which primarily involved running, accelerating, decelerating, cutting, tackling, and kicking movements. Furthermore, it is well known that high-force activities are a primary source of neuromuscular fatigue, therefore it is likely that the greater intensity of the muscle contractions in the resistance training session (i.e., 85% 1RM) resulted in greater mechanical or strain or metabolic disturbance, thus resulting in a greater decline in neuromuscular function than the SSGs. However, by +24h, there were no significant differences between protocols, suggesting that the order of SSG and resistance training does not appear to influence the neuromuscular response on the following day of training.

The only interaction effect for hormonal markers in the current study occurred for T, where it was revealed that at a group level, T concentrations were significantly higher at 0h during RES+SSG in comparison to the same time point during SSG+RES (between trial difference; +21.4 ± 26.7 pg·ml^{-1}; p <0.05; *moderate*). In addition, within-trial analyses revealed that there was a significant increase in the T:C ratio at 0h during RES+SSG (+112.9 ± 115.0 AU; p <0.05; *moderate*). However, there were no significant within-trial changes in T or C independently at 0h during either trial and no significant interaction effects between protocols for the T:C ratio or C (Table 15). Whilst little is known about the hormonal responses to SSG training, the finding that the T:C ratio significantly increased immediately after resistance training in combination with the significantly higher T concentration at 0h during RES+SSG in comparison to SSG+RES, may support previous literature in suggesting that resistance training drives acute changes in endogenous hormones which are reflective of an anabolic environment (Kraemer & Ratamess, 2005; Beaven, Gill, & Cook, 2008; McCaulley et al., 2009; Crewther et al., 2011b). Whilst selection of multi-joint exercises that recruit many muscle fibres (e.g., squats), performed at sufficiently high volumes and intensities are thought to be training variables that elicit this response, it is also thought that a high metabolic component to the resistance training session is another key factor that drives hormonal changes (Guezennec et al., 1986; Kraemer et al., 1990; Kraemer et al., 1991; Lu et al., 1997; Kraemer & Ratamess, 2005; McCaulley et al., 2009; Crewther et al., 2011b). For example, hypertrophy protocols high in total volume, with moderate loads (e.g., ~70 – 75% 1RM) combined with relatively short rest periods (≤2-min) have typically produced the greatest increases in T and C (Guezennec et al., 1986; Kraemer et al., 1990; Kraemer et al., 1991; Kraemer et al., 2003; Kraemer & Ratamess, 2005; McCaulley et al., 2009). Therefore, considering the content of the resistance training protocol in the current study was aimed at the development of strength, included large muscle mass exercises (i.e., the barbell back-squat, Romanian deadlift, and the hip thrust), and was at a relatively high volume and intensity (i.e., 60-min total training time; 85% 1RM), it could be that the metabolic stress accumulated from the training session was the variable that limited the magnitude of the within-trial T and C response at 0h during RES+SSG. Moreover, we programmed 4-min of rest between sets and exercises, and it is possible to theorise that if we had reduced the intensity (<85% 1RM) and the rest intervals (<4-min), but concomitantly increased the number of repetitions (>4), this may have increased the glycolytic demand during the resistance training session and may have resulted in a greater magnitude of within-trial change in T and C at this time point.

Within-trial analyses revealed that from baseline to +2h during both protocols, at a group level, T and C had significantly decreased whereas the T:C ratio significantly increased, with no interaction effects between protocols for any hormonal markers at this time point (Table 15). The declines in T and C independently at this time point are unsurprising as this follows the normal circadian declines reported throughout the day (Kraemer et al., 2001; Dimitriou, Sharp, & Doherty, 2002; Teo, McGuigan, & Newton, 2011). However, it is possible that hormonal concentrations may have been altered from normal daily values at this time point, and the significant within-trial increases in the T:C ratio at 2 hours post could be a direct response to training. However, the lack of non-exercise control data in the current study means this cannot be confirmed. Previous investigations into twice-daily training have reported that the performance of a morning resistance training session may alleviate the typical circadian declines in T throughout the day (Cook et al., 2014; Russell et al., 2016a), and there is an abundance of evidence that elevated T concentrations may support the neuromuscular system through various short-term mechanisms (e.g., motivation, second messenger signalling, neural activity, motor system function, and energy metabolism) (Crewther et al., 2011b). Therefore, altering this rate of decline could potentially create an environment later in the day when the ability to generate strength, speed, power, and overall performance is enhanced (Crewther et al., 2011a; Cook, Crewther, & Kilduff, 2013; Cook et al., 2014; Russell et al., 2016a). However, in the current study, despite the significantly higher T concentration at 0h with resistance training coming first in the sequence, by +2h there were no significant differences between protocols and no improvements in any functional markers of performance could be determined. Considering that previous studies have observed this effect of morning strength training (~08:00 – 09:00 hours) on afternoon performance (~14:00 – 15:00 hours) (Cook et al., 2014; Russell et al., 2016a), it is possible that the time of day at which the training sessions were performed in the current study (i.e., 17:30 and 20:30 hours) could be a reason for this. Concentrations of T and C have been shown to peak in the early morning before a gradual decline thereafter (Kraemer et al., 2001; Dimitriou, Sharp, & Doherty, 2002; Teo, McGuigan, & Newton, 2011). Therefore, it is possible that if the training sessions in the current study had been undertaken earlier in the day when circulating concentrations of T and C were likely to have been higher, this may have resulted in differences in the hormonal responses observed. Another consideration is that previous investigations into hormonal priming permitted a greater between-session recovery than the current study (6 hours vs 2 hours) (Cook et al., 2014; Russell et al., 2016a), which is likely to offer additional opportunities for replenishment of substrates and restoration of neuromuscular function (Fyfe, Bishop, & Stepto, 2014). Furthermore, it has been shown that repeated sprint running (6 × 40 m maximal shuttle runs with 20 s recovery) may also offset the daily circadian declines in T concentrations (Russell et al., 2016a). Therefore, it is possible that the SSG training also altered the typical hormonal concentrations at +2h, although again, a lack of non-exercise control data means this cannot be confirmed. Nevertheless, the manipulation of programming variables to elicit favourable hormonal profiles for a second daily training session could be an important consideration when scheduling soccer training, and further research in this area may be beneficial.

By 24 hours post training, at a group level, T, C, and the T:C ratio were near pre-values, and there were no significant interaction effects between protocols (Table 15), suggesting that the order of resistance and SSG training does not influence the concentrations of these hormones on the following day. Whilst the anabolic and anticatabolic effects of T are well documented, it is also thought to have an important function in glycogen resynthesis and partly mediate several mechanisms of muscular and metabolic recovery following exercise (Cormack, Newton, & McGuigan, 2008; Papacosta & Nassis, 2011; Sinnott-O'Connor et al., 2018). In addition, elevations in C beyond normal values are thought to inhibit components of inflammatory and immunological function, and C is widely used as a biomarker to indicate recovery status in athletes (Urhausen, Gabriel, & Kindermann, 1995; Viru & Viru, 2004; Papacosta & Nassis, 2011; Duclos & Tabarin, 2016). Given the opposing roles of T and C and their respective functions in regulating anabolic and catabolic activity, periods of excessive training load, competition, and psychological stress may reduce T but concomitantly increase C concentrations, resulting in a reduction in the T:C ratio (Cormack, Newton, & McGuigan, 2008; Ispirlidis et al., 2008; Rowell et al., 2017). Indeed, recent work in soccer has observed that the T:C ratio tends to respond inversely to training load and is associated with self-report measures of well-being across a season (Springham et al., 2021). Therefore, the lack of any between-trial significant differences in hormonal concentrations at +24h in the current study suggests that the order of SSG and resistance training may not impact the acute regulation of anabolism (i.e., tissue growth, substrate restoration, and recovery) or catabolism (i.e., tissue breakdown and metabolic regulation), which is perhaps unsurprising given that the combined training load was the same on both trials (Kraemer, Ratamess, & Nindl, 2017). This finding is consistent with the other measured variables in the current study, with no significant within- or between-trial effects observed for the markers of neuromuscular function (relative PPO and JH) or mood at 24 hours post-training (Table 14).

6.5.1 Applied implications

An important factor to consider when interpreting hormonal responses to exercise is that the magnitude and direction of change may be highly individual and protocol-dependent, and analyses of data at a group level may mask this (Jensen et al., 1991; Beaven, Gill, & Cook, 2008; Crewther et al., 2009a; Gaviglio et al., 2015). Indeed, the individual data presented in the current study for T (Figure 21 A and B), C (Figure 21 C and D), and the T:C ratio (Figure 21 E and F) supports this. For example, immediately after the first training session during both trials, the individual percentage changes in T ranged from -20 – 38% and -20 – 28% for the SSG+RES and RES+SSG trials, respectively (Figure 21 A and B). Large ranges in the immediate individual percentage changes from baseline were also evident for C concentrations (SSG+RES, -54 – 147%; RES+SSG, -51 – 102%) and the T:C ratio (SSG+RES, -54 – 107%; RES+SSG, -39 – 107%). Individual differences in hormonal responses to exercise may be related to several physiological and psychological mechanisms. Previous research suggests that training experience may influence the magnitude of post-exercise change in hormones (Kraemer & Ratamess, 2005), and it has been demonstrated that after resistance training, strength-trained athletes typically produce greater increases in T than endurance or non-trained individuals (Kraemer et al., 1992; Tremblay, Copeland, & Van Helder, 2004; Ahtiainen et al., 2004; Kraemer & Ratamess, 2005). Furthermore, the carryover between acute increases in T and enhanced physical performance appears to be stronger in elite athletic populations (Crewther et al., 2011a; Cook & Crewther, 2012a; Crewther et al., 2012). A likely explanation for this is that resistance training is well-known to contribute to the development and recruitment of the larger type II muscle fibres (Folland & Williams, 2007), and individual variability may be attributed to morphological differences (e.g., muscle fibre area) or genetics (e.g., muscle fibre distribution, receptor number, and binding capacity) (Crewther et al., 2009a). Furthermore, we cannot discount the potential impact of nutrition (Kraemer et al., 1998), psychological factors (Suay et al., 1999; Cook & Crewther, 2012a), social interactions (Archer, 2006), and motivation (Cook, Crewther, & Kilduff, 2013) on the responses observed.

The individual hormonal responses to the exercise protocols in this study described above may have important implications for those working in applied settings. Beaven, Gill, & Cook (2008) observed that when 15 elite rugby players performed four distinct resistance training protocols in a random order, there was a non-significant protocol effect on T concentration when considering all athletes as a homogenous group. However, when individual data were re-examined, a clear protocol-dependent effect was observed, whereby each athlete responded optimally to one or two of the training protocols, at least in terms of T response, with minimal responses to the others (Beaven, Gill, & Cook, 2008). Consequently, the same author group prescribed an individual resistance training program to another group of 16 amateur players based on the protocol that elicited the greatest individual T response, reporting significantly greater increases in strength (i.e., 1RM leg and bench press) in comparison to grouping players based on traditional single population approach (Beaven, Cook, & Gill, 2008). Whilst these data do not provide evidence that T is the primary driver of adaptation, it does demonstrate that

T may be able to be used as a marker for identifying individual training protocols to optimise functional gain. Another potential benefit of this approach could be to enhance motivation and performance during later training sessions (Cook, Crewther, & Kilduff, 2013; Cook & Beaven, 2013; Crewther et al., 2016), and may even influence subsequent match outcome (Crewther et al., 2013; Gaviglio & Cook, 2014; Gaviglio et al., 2014). It is acknowledged that the majority of previous work in this area has recruited rugby players, however, there may be an important practical relevance of identifying individual hormonal responses to various training sessions in soccer. This may provide useful information for which to inform individualised training programs, and the literature may benefit from future work in this area in soccer.

There was also considerable individual variability in the markers of CMJ performance in this study, namely JH (Figure 20 C and D) and relative PPO (Figure 20 E and F). Interestingly, there appeared to be smaller ranges of individual percentages changes from baseline noted immediately after SSG training in comparison to resistance training. For JH, the individual percentage changes from baseline to immediately post SSG training ranged from -25 – 8%, and from -22 – 3% after resistance training. For relative PPO, the immediate individual percentage changes from baseline ranged from -13 – 4% after SSG training, and from -13 – 0% after resistance training. A possible explanation for the greater individual variability in markers of neuromuscular function immediately after SSG training may be that the physical demands are less controlled in comparison to resistance training. Indeed, the resistance training session in this study was prescribed based on individual 1RM and highly structured in terms of exercises, sets, repetitions, and rest periods. In contrast, when prescribing SSGs even of the same format and conditions, the physical and physiological demands may vary (Clemente et al., 2021), which is likely to be influenced by a multitude of factors such as positional differences, individual effort, motivation, and aerobic fitness (Clemente, 2019a; Owen et al., 2020). In turn, it is unsurprising that if the physical and physiological demands varied between individuals, then this would impact the responses observed. Individual fatigue responses to team-sport matches have also been shown to be influenced by the baseline physical qualities of the players (i.e., aerobic fitness and lower limb strength), irrespective of the physical output during the match (Owen et al., 2015; Johnston et al., 2015b). These data highlight the importance of identifying the individual responses to training sessions and for practitioners to recognise that the same exercise stimulus may result in a broad range of inter-individual responses, which could inform individual training prescription or recovery strategies in subsequent activities throughout the week.

6.5.2 Limitations

It is acknowledged that there are several limitations in this study that should be considered when interpreting the results. Firstly, the collection of additional data may have provided a more detailed understanding of the physical demands and the responses to the training sessions in this study. During the SSGs, the training load metrics were limited to RPE, total distance, HSR (≥19.8 km.h^{-1}), and PlayerLoad™. Although these metrics are common in previous soccer literature (Ade, Harley, & Bradley, 2014; Barrett, Midgley, & Lovell, 2014; Russell et al., 2016b; Beenham et al., 2017; Owen et al., 2017b; Rowell et al., 2018) and in applied settings (Akenhead & Nassis, 2016), it is recognised that the collection of additional internal (e.g., HR) and external markers of training load (e.g., accelerations, decelerations, and running distances at lower speeds) may have been suitable for SSG format and the pitch size used (i.e., 4 vs 4 +GKs; 24 x 29 m). This may have provided a more comprehensive picture of the physical load imposed by the SSGs and provided practitioners with further reference by which to compare the physical demands to those seen in their practices. Furthermore, post-exercise elevations in BLa have been linked to elevations in T (Lu et al., 1997; Kraemer & Ratamess, 2005), therefore, blood sampling immediately after the SSG and resistance training sessions may have provided useful markers, as well as permitting analyses of additional variables such as CK concentration as an indicator of muscle damage. As alluded to previously, T and C concentrations exhibit circadian rhythmicity (Kraemer et al., 2001; Dimitriou, Sharp, & Doherty, 2002; Teo, McGuigan, & Newton, 2011), and the absence of a non-exercise control trial in this study means that we are unable to ascertain whether hormone concentrations were altered from typical values at the same time on a rest day. Furthermore, whilst we obtained salivary samples at +2h, due to logistical constraints we were unable to perform a full battery of tests at this time point which may have allowed a better interpretation of the readiness of the players to undertake the second training session of the day.

Another important consideration is that due to the logistical constraints of obtaining force platform measurements from numerous players immediately after a warmup or a training session, there are inevitable differences in the proximity of each assessment to the cessation of exercise. It is possible that individual differences in the proximity of each assessment to the end of training or the warm-up may have influenced CMJ performance and may have contributed to the individual variability reported in this study (Tsurubami et al., 2020). Other considerations related to the design of the study were that whilst we attempted to control the baseline condition of the players by permitting 72 hours of rest before test involvement, this is likely to be more rest than most elite teams schedule consistently during the season (Malone et al., 2015a; Owen et al., 2017a). Previous work in soccer has shown that the training load in the 3 days prior to a match may influence performance (Rowell et al., 2018). Therefore, if the players in the current study had trained or competed in the days prior to undertaking the training sessions, as is likely to happen in elite settings, this may have impacted both the performance of training and the responses observed.

Another consideration is that whilst the participants were instructed to follow their usual dietary routines in the days leading up to and during the study, there were no diet records kept or monitoring of hydration status. It is recognised that individual differences in nutrition and hydration may have influenced physical performance during the training sessions and the responses observed (Kraemer et al., 1998; Oliveira et al., 2017). Furthermore, although the SSG training sessions were subjectively performed under similar environmental conditions, and the resistance training was performed at an indoor training facility in a temperature-controlled environment, there was no detailed record of this to report in this study which is a limitation. Finally, it is important to emphasise that the time at which the training sessions were performed in the current study (i.e., 17:30 and 20:30 hours) is likely to be later than the time at which many full-time professional athletes train. Due to diurnal variations in physiological processes that may influence exercise performance (e.g., muscle and core temperature, oxygen consumption, ventilation, heart rate, and hormone secretion) (Atkinson, & Reilly, 1996; Deschenes et al., 1998; Teo, McGuigan, & Newton, 2011), it is possible that performing the training sessions earlier in the day may result in differences in training performance and the physiological responses. Consequently, practitioners would be advised to consider where they schedule double training days in their environment (e.g., time in the microcycle and time of day) and how this might relate to the results of the current study. Finally, it is recognised that the on-field warm-up prior to SSG training was relatively short (i.e., 5-min), and it is possible that this short time period did not fully elicit all the potential temperature and non-temperature related mechanisms of warm-up (Bishop, 2003a).

6.6 CONCLUSIONS AND PRACTICAL APPLICATIONS

Given the prevalence of scheduling multiple daily training sessions in soccer (Hoff & Helgerud, 2004; Enright et al., 2015; Cross et al., 2019), this study was designed to investigate the acute effects of manipulating the order of SSG and resistance training. In summary, comparisons between the two training sequences revealed that relative PPO was impaired to a greater extent immediately after the first training session during RES+SSG in comparison to SSG+RES (between trial difference; -2.69 ± 3.30 $W \cdot kg^{-1}$; $p < 0.05$; *moderate*). Furthermore, resistance training resulted in a significantly higher T concentration at 0h during RES+SSG in comparison to the SSG training during SSG+RES (between trial difference; $+21.4 \pm 26.7$ $pg \cdot ml^{-1}$; $p < 0.05$; moderate). However, by 24 hours post-training, there were no significant differences between protocols for any of the measurements taken, suggesting that the order of training does not influence the fatigue and recovery kinetics on the subsequent day (Table 14 and 15). In addition, the order of training did not appear to affect the subjective or objective physical demands of the SSGs, however, when scheduled after SSG training, the perceived effort during resistance training was significantly higher (RPE between-trial difference; $+0.9 \pm 1.1$ AU; $p < 0.05$; *moderate)*. These findings may be of interest to those responsible for designing soccer training programs, however, future research may be necessary to determine the effects of altering the training order on the molecular responses or the longer-term adaptations to concurrent training in team-sport settings. Nevertheless, several practical applications can be derived from this study:

- The order of SSG and resistance training sessions with sufficient between-session recovery time (i.e., ≥2 hours) does not appear to influence the perceived effort or the external demands during SSGs.
- When resistance training aimed at the development of lower-body strength is performed 2 hours after SSGs, the ability to complete the training session is maintained but the perceived effort is higher.
- Manipulating the order of SSG and resistance training with 2 hours of between-session recovery does not significantly influence neuromuscular, endocrine or mood responses 24 hours later, suggesting that practitioners can schedule either order without recovery being further compromised.

- There may be a highly individual response to training sessions in soccer, and the data presented in this study provides practitioners with a range of values that may be expected.

Chapter 7.

General Discussion

7.1 GENERAL DISCUSSION INTRODUCTION

Due to the necessity of soccer players to simultaneously maintain and develop multiple physical qualities and the challenges of organising concurrent training in soccer, the overarching aim of this thesis was to broaden and enhance our understanding of the acute responses to SSG training and its concurrent integration into a training program along with resistance training. After extensively reviewing the literature and identifying gaps in our current understanding of SSG and concurrent training in soccer, three research studies were conducted with differing aims and objectives but aligned to the same overall topic. A brief overview of each experimental chapter and the key findings are provided below, which will be expanded upon and linked together in the later stages of this final section of the thesis.

- Chapter 4 characterised the neuromuscular, endocrine, biochemical and mood responses to SSG training over a 24-hour period. Additionally, this study examined the between-repetition changes in physical demands during SSG training. The key findings of this study were:
    - The SSG training induced immediate fatigue as evidenced by *small – moderate* disturbances in neuromuscular function, mood, and CK, which in the case of neuromuscular function and CK persisted until the following morning when mood has returned to baseline.
    - However, markers of neuromuscular performance underwent a bimodal recovery pattern, whereby there was a temporary recovery of CMJ variables at 2 hours post-training, indicating that this may represent a time point in which additional training could be undertaken without performance being compromised.
    - The T:C ratio was elevated across all time points relative to baseline, which was mostly driven by reductions in C concentrations. However, there was a very individual hormonal response to training.
    - The external demands during the training session presented a gradual decline across repetitions, with the first SSG repetition consistently producing the highest outputs for the metrics analysed (i.e., total distance, Playerload^{TM}, and HSR) with *moderate – large* reductions thereafter.

- Chapter 5 compared the neuromuscular, endocrine and mood responses to a day consisting of SSG training (single session) vs a day consisting of SSG training plus resistance training session 2 hours later (double session).
    - The main finding of this study was that the addition of a lower body strength training session 2 hours after the SSGs resulted in *possibly – likely small* negative disturbances in neuromuscular, mood, and hormonal markers at 24 hours post, indicating additive fatigue effects.

- Finally, chapter 6 investigated the effects of manipulating the order of SSG and resistance training on the performance of training, and neuromuscular, endocrine and mood responses over a 24-hour period. The primary findings of this study were:
    - The order of SSG and resistance training did not affect the external load or the RPE during SSG training ($p > 0.05$). however, the RPE for resistance training was significantly higher when performed 2 hours after SSG training ($p < 0.05$).
    - Comparisons between the two training sequences revealed that whilst there were significant within-day differences in relative PPO and T, by 24 hours post-training, there were no significant between-protocol differences in neuromuscular, endocrine, or mood markers, indicating that training order does not influence the fatigue and recovery kinetics on the following day.

This section of the thesis will link, compare, and connect all of the experimental chapters and discuss the key findings of this thesis as a whole. Finally, practical applications will be suggested, and limitations that pertain to each of the studies in this thesis will be acknowledged and discussed.

7.2 SYNTHESIS OF RESEARCH FINDINGS

The SSG training protocol implemented in each of the experimental chapters was standardised (as described in section 3.3.1) and similar to the format used in an abundance of previous literature (Reilly & White, 2004; Sassi, Reilly, & Impellizzeri, 2004; Impellizzeri et al., 2006; Little & Williams, 2007; Rampinini et al., 2007c; Dellal et al., 2008; Kelly & Drust, 2008; Hodgson, Akenhead, & Thomas, 2014; Hulka, Weisser, & Belka, 2016; Beenham et al., 2017; Lacome et al., 2018). The physical demands of each SSG training session performed across this thesis are presented in Table 16. Overall, it seems that the training load during the SSGs was broadly similar within each chapter; each group of players consistently rated the training session as 'very hard' on the RPE scale used (Table 16). Previous studies quantifying training load at elite soccer clubs have reported that team average total distances on a given training day throughout the week range between ~2700 – 6700 m, and high-intensity distances (≥19.8 km.h^{-1}) of between ~3 – 250 m (Malone et al., 2015a; Owen et al., 2017a; Martín-García 2018b). However, this is highly dependent on how many days pre- or post-match the training session occurs, varies between playing positions, and is only descriptive of the teams studied. Nevertheless, this suggests that the overall training load the players experienced within the experimental chapters was broadly similar, or at least within the typical ranges to those seen in professional practises (Table 16). Furthermore, the average playing intensity (total distance covered per minute) during the SSGs ranged between 105 – 111 m·min^{-1} across the experimental chapters, which is similar to those reported by Lacome et al. (2018) during the same format of SSGs (i.e., 4 vs 4+GKs) in elite players (~105 m·min^{-1}), but higher than reported in amateur and junior players (~93 – 101 m·min^{-1}; Hodgson, Akenhead, & Thomas, 2014; Hulka, Weisser, & Belka, 2016; Casamichana, Bradley, & Castellano, 2018).

Table 16. The physical demands (mean ± SD) of each SSG training session across this thesis.

Chapter (playing standard)	Trial	RPE (AU)	Total distance (m)	HSR (m)	Playerload™ (AU)
Chapter 4 (professional)	SSG	7.1 ± 1.3	4388 ± 231	41 ± 30	483 ± 38
Chapter 5 (semi-professional)	Single	7.3 ± 0.8	4475 ± 397	21 ± 22	452 ± 59
	Double	7.7 ± 0.7	4315 ± 641	30 ± 35	444 ± 85
Chapter 6 (semi-professional)	SSG+RES	7.3 ± 1.0	4659 ± 611	36 ± 28	470 ± 72
	RES+SSG	7.6 ± 1.1	4660 ± 583	35 ± 26	465 ± 75

Abbreviations: RPE, rating of perceived exertion; HSR, high-speed running; AU, arbitrary units; SD, standard deviation; SSG+RES, small-sided games followed by resistance training, RES+SSG, resistance training followed by small-sided games.

Interestingly, it seems that the professional players in chapter 4 may have covered similar or lower total distances than the semi-professional players recruited in chapters 5 and 6, however, mean values for HSR and Playerload^{TM} were the greatest in the full-professional players (Table 16). Although discrete, this might suggest that the movement intensity was greater in the professional players and supports previous research which has suggested that elite players perform more HSR than sub-elite players in 11 vs 11 matches (Mohr, Krustrup, & Bangsbo, 2003; Mohr et al., 2008; Ingebrigtsen et al., 2012), despite total distances being similar (Mohr et al., 2008; Ingebrigtsen et al., 2012). Furthermore, during 5 vs 5 SSGs in elite players, Owen et al. (2020) found strong relationships (r = 0.66 – 0.88; *likely large – possibly very large*) between aerobic fitness (i.e., Yoyo intermittent recovery test level 1) and the external demands produced for similar metrics to those measured in the current thesis (i.e., total distance, HSR ≥19.8 km.h^{-1}, and total accelerometry load). However, it should be noted that in competitive games when the playing standard increases to the top professional leagues, studies have reported no differences in physical outputs (Bradley et al., 2010), or that lower-ranked teams may be required to perform more than their higher ranked counterparts (Di Salvo et al., 2009; Rampinini et al., 2009a; Bradley et al., 2013). Moreover, it is suggested that technical and tactical effectiveness are more important in determining team success over a season (Di Salvo et al., 2009; Rampinini et al., 2009a), and numerous confounding variables such as ball possession, game status, technical ability, and tactical approach may influence match running performance (Carling, 2013). Nevertheless, if any differences in the physical demands during the SSG training sessions did occur, these could be attributed to factors such as the quantity and quality of technical actions performed (Bradley et al., 2013) or differences in the physical qualities and training status of the players (Ingebrigtsen et al., 2012; Owen et al., 2020).

One of the objectives of chapter 4 was to further break down the external demands of the SSGs and assess the between-repetition changes in GPS metrics. The highest physical outputs were consistently observed during the first SSG repetition for each metric analysed, with *moderate – large* reductions thereafter. This finding supports previous literature which has reported that external load variables decline across SSG repetitions, which is independent of the number of players (i.e., 1 vs 1 – 7 vs 7), task constraints (e.g., touch limitations), and playing level (Dellal et al., 2011b; Dellal, Drust, & Lago-Penas, 2012; Clemente et al., 2017; Clemente et al., 2019b; Clemente et al., 2020; Bujalance-Moreno et al., 2020; Younesi et al., 2021). Similar observations have been noted during 11 vs 11 match play, whereby physical outputs decline across halves and in the final stages of each half (Bradley et al., 2009; Di Salvo et al., 2009;

Carling & Dupont, 2011; Akenhead et al., 2013; Russell et al., 2014; Barrett et al., 2016), and these declines appear to be synonymous with declines in technical or skill-related performance (Rampinini et al., 2008; Rampinini et al., 2009a; Russell, Rees, & Kingsley, 2013). Therefore, the declines in external load metrics across the SSG repetitions in chapter 4 might further support and provide a functional marker for the consistent declines in neuromuscular function noted immediately post SSG training in this thesis. Within-match fatigue has typically been associated with peripheral mechanisms, with various ionic and metabolic perturbations (e.g., Pi, H^+, Ca^{2+}, Na^+, K^+) and depletion of substrates (e.g., ATP, PCr, or glycogen) being implicated in previous research (Mohr, Krustrup, & Bangsbo, 2005; Mohr et al., 2016b). However, there is considerable evidence that central mechanisms occurring at the spinal or supraspinal level may contribute significantly to soccer-related fatigue (Rampinini et al., 2011; Brownstein et al., 2017; Goodall et al., 2017; Thomas et al., 2017), which is discussed later in this section.

The primary aim of experimental chapter 4 in this thesis was to characterise the neuromuscular, biochemical, endocrine and mood responses to SSG training over 24 hours in professional players. This was identified as a clear gap in the literature as a very limited number of studies have investigated the impact of soccer training on the responses of the markers outlined above, and to the author's knowledge, no other studies have profiled responses to SSG training over 24 hours. This is somewhat surprising, given the popularity of SSGs and the plethora of research that has focused on the physical demands (e.g., GPS data), the immediate physiological and perceptual responses (e.g., HR, BLa, and RPE) and the chronic adaptations to SSG training (reviewed in section 2.3.2). In addition, there has been considerable focus in the literature on the fatigue and recovery time course following 11 vs 11 match play (e.g., Andersson et al., 2008; Magalhães et al., 2010; Rampinini et al., 2011; Nedelec et al., 2012; Brownstein et al., 2017), therefore, it was determined that characterising the responses to training may further support practitioners in informing training design. Considering that physically demanding training sessions are often performed in proximity to each other (i.e., on the same day and consecutive days) in soccer (Morgans et al., 2014; Malone et al., 2015a; Martín-García et al., 2018b; Cross et al., 2019), the results of chapter 4 may have significant implications for the programming and sequencing of additional training sessions performed within a microcycle, and certainly informed the design of subsequent experimental chapters in this thesis.

The immediate neuromuscular response to the SSG training session in chapter 4 was characterised as a decline in both JH (-8.6 ± 12.4%; *possibly moderate*) and relative PPO (-2.1 ± 3.8%; *possibly small*). This appears to be of a similar or a greater magnitude to the immediate declines in CMJ variables in response to the SSG training sessions repeated in chapter 5 (single, JH, -4.5 ± 8.1%, *possibly small*, relative PPO, -0.5 ± 6.3%, *trivial*; double, JH, -5.5 ± 11.9%, *likely small*, relative PPO, -2 ± 6.2%, *possibly small*) and chapter 6 (JH, -5.6 ± 7.2%; relative PPO, -1.5 ± 4.9%). The initial impairments in CMJ height across the experimental chapters appear to be similar to those reported by Brownstein et al. (2017) at 10 – 60 minutes after a 90-min semi-professional match (-5 ± 8%), but of a lesser magnitude than the declines (~12%) reported by Magalhães et al. (2010) and Thomas et al. (2017) immediately after a professional match and a simulation protocol in semi-professional players, respectively. Furthermore, a recent study by Ade et al. (2021) in a similar cohort of elite and sub-elite players reported that a 12 – 24-min position-specific soccer training drill aimed at the development of speed endurance immediately impaired CMJ height by ~4%. Whilst the origin of neuromuscular fatigue cannot be derived from jumps, several studies have investigated the aetiology of neuromuscular fatigue after 90-min of real (Rampinini et al., 2011; Brownstein et al., 2017) and simulated (Goodall et al., 2017; Thomas et al., 2017) matches, concluding that soccer-related neuromuscular fatigue is underpinned by a combination of central and peripheral mechanisms. Furthermore, significant central and peripheral fatigue manifests as early as half time (i.e., 45-min) (Goodall et al. 2017), which is similar to the playing duration of the SSGs in this thesis (i.e., 42-min). Considering that CMJ height has been reported to present a similar decline and recovery time course to the other direct markers of neuromuscular function after soccer (Thomas et al., 2017; Brownstein et al., 2017), this suggests it may be a practical and sensitive surrogate marker for assessing the neuromuscular response to soccer activity. Therefore, whilst the precise mechanisms of neuromuscular fatigue were not elucidated in this thesis and several mechanisms may be responsible for a loss of force (reviewed in section 2.5), on the current evidence it seems likely that the initial declines in CMJ variables in this thesis may be attributed to a combination of intramuscular biochemical changes (e.g., H+, Pi, pH) and mechanical strain, which might stimulate group III/IV muscle afferents and provide inhibitory feedback to the CNS and reduce motor drive (Sidhu et al., 2017; Hureau et al., 2022).

A key finding of chapter 4 was that neuromuscular function underwent a bimodal recovery pattern in response to the SSG training, whereby CMJ variables had recovered after 2 hours (JH, +0.2 ± 5.6%, *trivial*; PPO, +1.3 ± 3.6%, *trivial*), before a secondary decline on the following morning (JH, -6.8 ± 6.3%, *likely small*; PPO, -1.7 ± 3.4%, *possibly small*). This neuromuscular response has been observed after several other repetitive SSC activities, such as maximal speed training (Johnston et al., 2015a), drop jump training (Dousset et al., 2007), AFL matches (Cormack, Newton, & McGuigan, 2008) and soccer matches (Andersson et al., 2008). Whilst the underpinning mechanisms of this bimodal recovery pattern were not directly studied, it seems likely that the recovery observed at 2 hours post was due to the removal of metabolites that were initially present, but before initiation of the inflammatory process which would be expected to be underway after 24 hours (Dousett et al., 2007; Johnston et al., 2015a). This theory is further supported by the *likely large* elevation in BLa immediately after the SSGs which had dissipated by 2 hours post, and whilst BLa is not a direct marker of metabolic fatigue, it may be considered as an indicator of metabolite accumulation (Skurvydas et al., 2006). The application of this finding is that if multiple training sessions are performed on the same day (e.g., SSG and resistance training), as is often the case in professional soccer (Cross et al., 2019), then this 2 hours post time point may represent a superior window for additional high-intensity training than immediately or at 24 hours post. Theoretically, if athletes undertook a second daily training session with impaired neuromuscular function, then this would limit their ability to perform the high-intensity explosive movements required to recruit the high threshold motor units necessary for inducing the neural adaptations associated with strength, power, and speed (Tan, 1999; Tannerstedt, Apró, & Blomstrand, 2009). However, after completion of this study, it was recognised that it was unknown to what extent the performance of an additional daily training session may have on neuromuscular, endocrine, or mood markers at 24 hours post. Therefore, this prompted further investigation in experimental chapter 5, by comparing a training day consisting of SSG training (single session) to a day consisting of SSG training with the addition of a lower body resistance training session 2 hours later (double session).

An interesting finding in this thesis is that the single training session in experimental chapter 5 did not impair CMJ performance at 24 hours post-training in the semi-professional players. This is a finding that contrasts with the results of experimental chapter 4 and previous studies (reviewed in section 2.8.1) which have reported that CMJ height is reduced by ~4% on the day after high-intensity soccer training sessions (Sjökvist et al., 2011; Ade et al., 2021). The declines in CMJ variables at 24 hours post in chapter 4 are likely to be attributed to muscle damage and the subsequent inflammatory response, which is supported by the increases in CK found at this time point (+39 ± 52%; *very likely small*). Previous investigations examining the neuromuscular response after soccer have reported that whilst central processes originating at the spinal or supraspinal level contribute significantly to the immediate declines in neuromuscular function, the typically slower recovery of peripheral fatigue indicators suggests that this may primarily explain the delayed recovery in the days that follow (Rampinini et al., 2011; Thomas et al., 2017). Therefore, considering that the physical demands during SSGs involve repetitive high-force eccentric and SSC activities (e.g., accelerations, decelerations, changing direction, jumping, kicking, tackling, and body contacts), which are known to have the potential of inducing muscle damage and reduce neuromuscular function 24 hours later (Bloomfield et al., 2007; Ispirlidis et al., 2008; Nedelec et al., 2014; de Hoyo et al., 2016; Hader et al., 2019), it could be theorised that the professional players might have performed more of these actions at a greater intensity than their semi-professional counterparts in chapter 5. Where comparisons in external demands between chapter 4 and the single session in chapter 5 can be drawn, it seems that although discrete, this might have been reflected in the comparatively higher values for Playerload™ in chapter 4 (483 ± 38 AU) compared to chapter 5 (452 ± 59 AU). However, whilst Playerload™ is considered a marker of the total 'mechanical stress' imposed on players and calculated from the 1000 Hz accelerometer as a summation of acceleration in each anatomical plane of motion (Cummins et al., 2013; Beenham et al., 2017), it is recognised that capturing additional GPS metrics during SSG training across this thesis may have been beneficial to facilitate comparisons between the experimental chapters, which is a limitation and discussed in section 7.4. In particular, high-intensity changes in velocity may impose distinct physiological and mechanical stresses on players (Harper, Carling, & Kiely, 2019); the metabolic cost during acceleration is greater than continuous speed running (di Prampero et al., 2005; Osgnach et al., 2010) and high-intensity decelerations involve eccentric muscle contractions with a high force braking ground reaction component (McBurnie et al., 2022). These actions are well known to predispose the lower limb musculature to structural damage, such as myofibrillar, cytoskeletal, and Z-line disruption, which is thought to manifest as LFF and impair the E-C coupling process (Clarkson & Sayers, 1999; Fridén & Lieber, 2001; Prasartwuth et al., 2006).

A consistent finding across this thesis is that mood score was disturbed immediately after SSG training. Relative to baseline, *moderate* increases in mood score were evident in immediately after SSG training in chapter 4 (+47 ± 81%; *likely moderate*), chapter 5 (single, +54 ± 80%, *likely moderate*; double, + 38 ± 30%, *likely moderate*) and chapter 6 (SSG+RES; +40 ± 60%; *moderate*). This suggests that the immediate perceptual response to the SSG training was similar within each chapter and might support previous literature in suggesting that self-report questionnaires provide a sensitive, practical, and cost-effective method of assessing the responses to training load (Thorpe et al., 2015; Gallo et al., 2017; Shearer et al., 2017). Furthermore, in experimental chapter 4, the alleviation in mood at 2 hours post SSG training (+27 ± 77%; *likely small*) in comparison to the immediate-post changes (+47 ± 81%; *likely moderate*) may further support the efficacy of this time point for further training if multiple daily sessions wish to be implemented. However, mood score did not always follow the same recovery pattern as neuromuscular variables. After 24 hours of recovery in experimental chapter 4 and the double training day in chapter 5, mood score had returned to baseline when CMJ variables were still disturbed. This supports previous literature in suggesting that subjective questionnaires should be used in conjunction with other objective markers of fatigue (Saw, Main, & Gastin, 2016; Brownstein et al., 2017). Moreover, due to the varied mechanical, metabolic and cognitive demands of soccer and the multi-factorial nature of fatigue, a comprehensive battery of tests is recommended to gain a broad understanding of an athlete's response to training load and their psychological readiness to undertake training or competition (Twist & Highton, 2013; Brownstein et al., 2017).

Whilst there was considerable individual variability in the hormonal responses to the SSG training sessions across this thesis (see section 7.3), at a group level, immediately after the SSGs in experimental chapter 4 there were *possibly small* increases in T (+11 ± 40%) and decreases in C (-17 ± 81%), which resulted in a *possibly moderate* increase in the T:C ratio (+67 ± 81%). In experimental chapter 5, there were also *possibly – likely small* immediate elevations in the T:C ratio immediately after the SSGs (single, +36 ± 74%, *likely small*; double, +20 ± 46%, *possibly small*), which were mostly driven by reductions in C, but any rises in the T:C ratio in chapter 6 were not significant (SSG+RES; +28 ± 50%; p >0.05). Furthermore, when examining the immediate changes in each hormone independently, in chapter 5 there were *trivial* changes in T (single, +2 ± 18%; double, +2 ± 19%), *possibly small* and *trivial* changes in C (single, -7 ± 75%, *possibly small*; double, -3 ± 66%, *trivial*), and non-significant changes for either hormone in response to the SSG training in chapter 6 (T, -2 ± 18%, p >0.05; C, -12 ± 67%, p >0.05). Whilst the experimental chapters within this thesis were the first to examine the hormonal responses to this type of training, a recent meta-analysis by Dote-Montero et al. (2021) reported that T and C concentrations both tend to significantly rise immediately after a single bout of HIIT, before returning to baseline after ~30 – 60-min, which is independent of the exercise mode (e.g., running, cycling, or swimming). Several factors may explain why there was not a greater immediate and consistent group increase in both T and C in response to SSG training across the experimental chapters in this thesis. Previous authors have suggested changes in T and C after exercise may be driven by a stress response as a result of metabolic accumulation (Lu et al., 1997; Spiering et al., 2008b; McCaulley et al., 2009; Walker, Ahtiainen, & Hakkinen, 2010), and significant relationships between increases in BLa and post-exercise elevations of T and C concentrations have been reported (West et al., 2014a). Therefore, the relatively low absolute changes in BLa measured after the SSGs in chapter 4 in comparison to previous literature (McCaulley et al., 2009; Coutts et al., 2009; Köklü et al., 2011), coupled with the gradual decline in playing intensity across repetitions, may indicate that there was a shift from anaerobic to aerobic metabolism over the time course of the SSG training session. Therefore, future work should establish the responses of T and C to other formats of SSGs, with varying pitch sizes, player numbers, and work-to-rest ratios. Another factor to consider is that changes in T and C may not only be driven by a physical stimulus but also psychological factors and social interactions (Suay et al., 1999; Archer, 2006; Cook & Crewther, 2012a). Considering that SSGs are fundamentally a competitive activity between opposing players, numerous contextual factors such as the game result and perceived individual performance may have had an impact on the changes in T and C.

It has previously been suggested that individual training status and experience may influence the response of the endocrine system to exercise (Kraemer & Ratamess, 2005; Dote-Montero et al., 2021), and studies have shown that elite athletes produce greater post-exercise changes in T than non-elite populations (Kraemer et al., 1992; Tremblay, Copeland, & Van Helder, 2004; Ahtiainen et al., 2004). Therefore, as described above, the possibly greater magnitude of the group mean increases in T and the T:C ratio in chapter 4 in comparison to chapters 5 and 6 may partially be attributed to differences in the playing level (i.e., professional vs semi-professional). However, a factor that should be considered is that by following the teams normal training schedules, there were differences in the time that the training sessions were performed; the SSG training session began at 10:30 hours in experimental chapter 4 and at 17:30 hours in experimental chapters 5 and 6. Considering that T and C concentrations exhibit circadian rhythmicity, with a peak in the early morning before a gradual decline thereafter (Kraemer et al., 2001; Dimitriou, Sharp, & Doherty, 2002; Teo, McGuigan, & Newton, 2011), this may limit the comparisons of changes in hormone concentrations between experimental 4 and those in chapters 5 and 6. Furthermore, as mentioned above, in agreement with previous literature (Beaven, Gill, & Cook, 2008; Gaviglio et al., 2015), analyses of individual participant data revealed that there were large individual changes in both T and C, which varied in both the direction and magnitude of change and discussed in section 7.3.

Concentrations of T and C in experimental chapter 4 were both found to be reduced from baseline values when measured at +2h (*likely moderate – large effects*), however, the T:C ratio was above baseline values (+130 ± 102%; *likely large*). Whilst we did not obtain saliva samples at 2 hours post in chapter 5, the same hormonal pattern was observed during both trials in chapter 6, where significant within-trial declines in T (SSG+RES, -21 ± 10%, *moderate;* RES+SSG, -14 ± 11%, *moderate*) and C (SSG+RES, -54 ± 18%, *large;* RES+SSG, -44 ± 20%, *large*) were found at 2 hours post, and the T:C ratio was above baseline values (SSG+RES, +95 ± 84%, *large;* RES+SSG, +78 ± 79%, *large*). The declines in T and C independently at 2 hours post in both chapters were expected due to the normal circadian declines reported throughout the day (Kraemer et al., 2001; Dimitriou, Sharp, & Doherty, 2002; Teo, McGuigan, & Newton, 2011). Furthermore, concentrations of T and C have been shown to decline below baseline values by 2 hours after HIIT protocols (Dote-Montero et al., 2021). However, it cannot be discounted that the performance of training in the current thesis may have offset the natural circadian patterns of T and C at the 2 hours post this time point, although, a lack of non-exercise control data means this cannot be confirmed. Furthermore, the consistent *large* elevations in the T:C ratio found at 2 hours post in chapters 4 and 6 in this thesis may be noteworthy in supporting the efficacy of this time point for undertaking additional training, considering that an anabolic hormonal milieu may support neuromuscular performance through several non-genomic functions (e.g., increased cognitive function, motivation, energy metabolism, and neural activity) (Crewther et al., 2011b).

In the two trials in this thesis where only SSG training was performed (i.e., chapter 4 and the single trial in chapter 5), after 24 hours of recovery, at a group level the same hormonal responses were observed, where T concentrations were at baseline values (*trivial*), and C concentrations were below (*possibly – likely small*), resulting in *possibly small* increases in the T:C ratio. In both studies, these declines in C on the following day in comparison to baseline are interesting findings and may be related to anticipatory rises in C prior to undertaking the SSG training. Many previous studies have reported that C concentrations are higher on a competition day before the start of the warm-up relative to the same time of day on a neutral non-competition day (Passelergue & Lac, 1999; Gonzaalez-Bono et al., 1999; Suay et al., 1999; Salvador et al., 2003; Alix-Sy et al., 2008; Filaire et al., 2009). This is thought to reflect a psychophysiological mechanism influenced by cognitive anticipation and anxiety; used by some athletes as an arousal and coping mechanism to manage pre-competition stress. On examination of the individual data presented within each chapter, it seems that if this anticipatory mechanism did occur it may have been more pronounced in some participants in comparison to others. Indeed, the absolute values of C at baseline had a greater standard deviation than those observed at 24 hours post, both in in chapter 4 (mean ± SD; baseline, 0.539 ± 0.281 $ug \cdot dl^{-1}$; +24h, 0.424 ± 0.161 $ug \cdot dl^{-1}$) and in chapter 5 (mean ± SD; baseline, 0.538 ± 0.210 $ug \cdot dl^{-1}$; +24h, 0.457 ± 0.158 $ug \cdot dl^{-1}$), indicating a greater individual variability in pre-exercise concentrations of C. Although we were not assessing actual competitive match play here, it is possible to theorise that SSG training may evoke a similar response. Indeed, the players were informed of the training protocol before taking part in the study, therefore, they knew that they were going to be competing against their teammates in a physically and technically demanding training session on that day under the supervision of the team coach.

Concentrations of CK were elevated from baseline across all time points in response to the SSG training in experimental chapter 4. Increases were observed immediately (+41 ± 39%; *very likely small*), which peaked at 2 hours post (49 ± 48%; *possibly moderate*), and remained above baseline at 24 hours post (+39 ± 59%; *very likely small*). Typical increases in CK seen immediately post 90-min soccer matches are ~75 – 250% of baseline values, before a peak (~125 – 350%) that occurs between 24 – 48 hours, and a return to near baseline generally after ~72 – 96 hours, depending on the magnitude of the peak (Nedelec et al., 2012; Silva et al., 2018). The comparatively lower increase in CK after the SSGs in comparison to matches may be explained by differences in both the duration of activity (i.e., 42-min vs 90-min) and high-intensity running distances. Indeed, both HSR (19.8 – 25.2 $km \cdot h^{-1}$; ~500 – 1200 m) and sprinting (≥25.2 $km \cdot h^{-1}$; ~100 – 450 m) distances are known to be far greater during match play in comparison to the SSGs (Bradley et al., 2009; Di Salvo et al., 2009), and these actions are also known to significantly contribute to post-match incidences of muscle damage and declines in neuromuscular function (Thorpe & Sunderland, 2012; de Hoyo et al., 2016; Hader et al., 2019). Nevertheless, the increases in CK observed in chapter 4 indicates that the SSG training session implemented across this thesis has the potential of inducing muscle damage despite low volumes of HSR (i.e., 41 ± 30 m), therefore, was likely a result of repeated accelerations, decelerations, directional changes, technical actions, or physical contact associated with SSGs (Ispirlidis et al., 2008; Hodgson, Akenhead, & Thomas, 2014; Beenham et al., 2017; Lacome et al., 2018). This finding may have significant implications for the sequencing of additional training activities performed within a microcycle, as further training in the presence of muscle damage may reduce subsequent training performance which, in turn, may inhibit adaptations to concurrent training over a longer period (Fyfe, Bishop, & Stepto, 2014; Doma, Deakin, & Bentley, 2017). Another interesting finding is that CK peaked at the 2-hour post time point in chapter 4 when CMJ variables had returned to baseline; a finding that raises questions as to whether changes in CK concentration are reflective of neuromuscular function. Indeed, a poor temporal relationship between CK and the recovery of muscle function has previously been reported after exercise-induced muscle damage (Margaritis et al., 1999), which further supports the need for a comprehensive battery of tests to ascertain the varied and multifactorial nature of fatigue (Twist & Highton, 2013; Brownstein et al., 2017).

Due to the multifaceted match requirements of soccer reviewed in section 2.2 of this thesis, concurrent training methods are typically implemented to target the multiple physical qualities pertinent to successful performance (Stølen et al., 2005; Morgans et al., 2014; Cross et al., 2019). Due to the high fixture demand in soccer, this leaves restricted training time, and players must maintain and develop multiple physical qualities simultaneously along with engaging in technical and tactical training (Morgans et al., 2014). Strength and power are fundamental physical qualities in soccer for many reasons, outlined in detail in previous sections of this thesis (see sections 2.3.3, 5.1, and 6.1). Therefore, resistance training is often performed in proximity to on-field training in soccer (i.e., on the same day and within 24 hours of each other) (Enright et al., 2015; Cross et al., 2019). Survey data from team sports practitioners has revealed that 78 – 89% of all resistance training sessions are prescribed on the same day as on-field training, and in soccer, 92% of respondents reported that they scheduled resistance training following on-field training (Cross et al., 2019). However, this concurrent training paradigm is often associated with an 'interference effect', whereby strength or cardiorespiratory adaptations are attenuated when aerobic training is performed alongside resistance training (Hickson, 1980; Wilson et al., 2012; Fyfe et al., 2016; Doma et al., 2019; Lee et al., 2020). Whilst the blunting of signalling pathways responsible for adaptation is one mechanism commonly explored to explain this trend, it is likely that acute declines in performance induced by a prior training session or day may inhibit the performance of the next via residual fatigue and/ or substrate depletion (Fyfe, Bishop, & Stepto, 2014; Doma, Deakin, & Bentley, 2017). Concurrent training research has typically examined the interactions between traditional aerobic training (i.e., steady-state or interval running or cycling) and resistance training, however, this is not representative of the varying demands and diverse contractile activity of typical team-sport training sessions (e.g., SSGs). This creates an important challenge when designing soccer training programs, and indeed, experimental chapter 4 revealed that an SSG training session induces negative disturbances in markers of neuromuscular function, muscle damage, and mood which may persist for 24 hours. However, it was determined that in order to take advantage of the bimodal recovery pattern of neuromuscular function observed in chapter 4, the performance of a lower body strength training session may not be compromised when undertaken 2 hours after SSG training, yet it was unclear what effect the addition of a second daily training session may have on the fatigue and recovery status of the players on the following day. Therefore, experimental chapter 5 compared the 24-hour neuromuscular, endocrine and mood responses to a training day consisting solely of SSG training (single session) to a day consisting of SSGs and a lower body strength training session 2 hours later (double session).

As described and discussed earlier in this discussion, the SSG training on both trials in experimental chapter 5 induced evidence of immediate fatigue, with *small* decreases in JH and *moderate* disturbances in mood, with no notable between-trial differences at this time point. This is unsurprising, as the training load metrics recorded during the SSG training sessions in chapter 5 were similar between trials (Table 16; $p > 0.05$). However, between-trial comparisons (single vs double) revealed that the addition of a lower body strength training session resulted in further *small* impairments in CMJ performance (between-trial difference; relative PPO, -2.5 ± 2.2 $W \cdot Kg^{-1}$; JH, -1.3 ± 2.0 cm), mood ($+4.6 \pm 6.1$ AU), and endocrine markers (T, -15.2 ± 6.1 $pg \cdot ml^{-1}$; C, $+0.072 \pm 0.034$ $ug \cdot dl^{-1}$; T:C, -96.6 ± 36.7 AU) at 24 hours post, indicating additive fatigue effects. Even when performed as a single training session, heavy resistance exercise similar to the protocol implemented across this thesis has been shown to compromise quadriceps maximal force production (~21 – 28%), VA (~8%), contractile function (~50%), and elevations in CK, perceived fatigue and muscle soreness for up to 24 – 72 hours post-training (Thomas et al., 2018; Marshall, Cross, & Haynes, 2018; Metcalf, Hagstrom, & Marshall, 2019; Cross et al., 2022). Therefore, likely explanations for the added fatigue 24 hours after the double training session in chapter 5 are that the additional mechanical strain and metabolic stress of the lower body resistance training induced further muscle damage, inflammation, metabolic and ionic disturbances, or declines in CNS function (Byrne et al., 2004; Allen, Lamb, & Westerblad, 2008; Taylor & Gandevia, 2008; Johnston et al., 2015a).

The results of experimental chapter 5 conflict with previous studies that have assessed the effects of performing twice-daily resistance training (Nosaka & Newton, 2002), plyometric training (Skurvydas, Kamandulis, & Masiulis, 2010a), sprint cycle training (Skurvydas, Kamandulis, & Masiulis, 2010b) and combined speed and resistance training sessions (Johnston et al., 2016). These studies have reported that in comparison to a single training bout, neuromuscular performance and markers of fatigue were not further exacerbated following twice-daily training (Nosaka & Newton, 2002; Skurvydas, Kamandulis, & Masiulis, 2010a; Skurvydas, Kamandulis, & Masiulis, 2010b; Johnston et al., 2016). However, the findings of chapter 5 may partly be supported by recent work by Cross et al. (2022), who reported that the addition of a resistance training session 1-hour after an intermittent sprint protocol resulted in a greater decrement in quadriceps contractile function (55 ± 9% vs 36 ± 11%). However, it should be noted that this did not alter the recovery time course, and all variables measured in this study (i.e., quadriceps contractile function, CK, perceived soreness and fatigue) recovered after 48 hours, independent of the number of sessions performed (Cross et al., 2022). Factors that may explain the discrepancy in the literature are the training volume and exercise modality. Notably, the studies previously mentioned that reported no differences between single and double training days implemented shorter training protocols that were similar in contractile activity and energy requirements (e.g., maximal sprints, plyometrics, and resistance training) (Nosaka & Newton, 2002; Skurvydas, Kamandulis, & Masiulis, 2010; Johnston et al., 2016). Conversely, the SSGs in chapter 5 and the intermittent sprint protocol implemented by Cross et al. (2022) were of a relatively high total running distance (Chapter 5; single, 4315 ± 641 m; double, 4475 ± 397; intermittent sprint protocol, 6520 ± 867 m) and total training duration (SSGs, 60-min; intermittent sprint protocol, 60-min). Therefore, it might be that implementing concurrent training sessions that are relatively high total volume (i.e., distance and duration), have a significant aerobic energy contribution, and are diverse in contractile activity could be factors that exacerbate the fatigue response during concurrent training, which in turn, might intensify the interference effect due to inhibitions in subsequent training performance. In support of this, many previous concurrent training studies reporting an interference effect have incorporated running, and less often cycling, as the endurance training modality (Leveritt et al., 1999; Wilson et al., 2012; Fyfe, Bishop, & Stepto, 2014). It has been suggested that this may be related to the similarity in the muscle contractions between cycling and many strength outcome measures (i.e., primarily concentric), as well as the greater eccentric contractions and muscle damage associated with running in comparison to cycling (Leveritt et al., 1999; Wilson et al., 2012; Fyfe, Bishop, & Stepto, 2014).

With regards to the hormonal markers measured in experimental chapter 5, whilst there were very individual responses noted immediately after SSG training, as demonstrated by large ranges of individual percentage changes from baseline for both T (single, - 20 – 36%; double, -20 – 38%), and C (single, -57 – 163%; double, -51 – 147%), there were no between-trial differences at a group level. However, after 24 hours, the addition of the resistance training session appeared to have decreased concentrations of T (group mean between-trial difference*;* -15.2 ± 6.1 pg·ml-1; *likely small*) but increased concentrations of C (+0.072 ± 0.034 ug·dl-1; *likely small*), resulting in a reduction in the T:C ratio (-96.6 ± 36.7 AU; *very likely small*). Recovery from strenuous exercise involves a complex interplay between several physiological mechanisms that restore normal homeostatic function (e.g., replenishment of metabolic substrates, removal of wastes, regeneration of damaged tissues, and restoration of neuromuscular function) and assist with the responses and adaptations to physiological stress, and some of these mechanisms are, in part, thought to be mediated by T and C (Kraemer, Ratamess, & Nindl, 2017). Given the opposing roles of T and C and their respective functions in regulating anabolism (i.e., tissue growth, substrate restoration, and recovery) and catabolism (i.e., tissue breakdown and metabolic regulation), periods of excessive training load, competition, and psychological stress have been shown to reduce T but concomitantly increase C, resulting in a reduction in the T:C ratio (Cormack, Newton, & McGuigan, 2008; Ispirlidis et al., 2008; Rowell et al., 2017). Indeed, the T:C ratio is commonly considered an indicator of athlete readiness (Urhausen, Gabriel, & Kindermann, 1995; Papacosta & Nassis, 2011; Sinnott-O'Connor et al., 2018), and relationships between the T:C ratio and perceptual measures of fatigue and overtraining have previously been reported (Adlercreutz et al., 1986; Maso et al., 2004; Springham et al., 2021). Therefore, the finding that the T:C ratio was lower at 24 hours after the double in comparison to the single training session day provides another objective marker in support of the declines in neuromuscular function and mood in chapter 5. However, as previously mentioned, given the possible anticipatory rise in C at baseline prior to undertaking SSG training and the high individual variability, it is acknowledged that changes in hormones might have been influenced by psychosocial rather than purely physiological mechanisms and are highly individual, which should be considered when interpreting the results. Furthermore, as saliva samples were only obtained across three time points in chapter 5 (i.e., pre, 0h, and +24h) and are known to display diurnal rhythmicity (Teo, McGuigan, & Newton, 2011), it is recognised that obtaining further measures at additional time points (e.g.,

+2h, +48h) to permit a full time course of change may have enhanced our understanding of the hormonal secretion patterns in response to the training days.

The design of experimental chapter 5 in this thesis was informed by the findings of chapter 4 and added a lower body resistance training session at the 2 hours post time point identified as suitable for undertaking additional training due to the temporary recovery of neuromuscular function observed. Furthermore, this concurrent training design (i.e., on-field training followed by resistance training with ~1 – 2 hours of between-session recovery time) is reflective of a typical training day in team sport (Enright et al., 2015; Cross et al., 2019). In summary, chapter 5 concluded that on-field training consisting of SSG training combined with lower body strength training 2 hours later resulted in *small* disturbances in neuromuscular performance, mood, and endocrine markers over a 24-hour period in comparison to SSG training alone. However, it was unknown if altering the training order might have an impact on the responses observed. Several studies have examined the acute effects of the altering the order or sequence of concurrent training due to its potential influence on the interference effect (Taipale & Häkkinen, 2013; Schumann et al., 2013; Taipale et al., 2014; Eklund et al., 2016; Jones et al., 2017). However, as alluded to above, the resistance and cardiorespiratory components of the concurrent training sessions often vary considerably from those commonly performed during field-based team sports. For example, the resistance training often involves a single exercise in combination with cycling-based aerobic exercise (Schumann et al., 2013; Eklund et al., 2016), or a number of resistance exercises in combination with steady-state running (Taipale & Häkkinen, 2013; Taipale et al., 2014; Jones et al., 2017). Furthermore, the endurance and strength loadings implemented in previous literature are often performed within a single session (i.e., no between-session recovery time) and have recruited untrained or recreationally active participants (Taipale & Häkkinen, 2013; Schumann et al., 2013; Taipale et al., 2014; Eklund et al., 2016; Jones et al., 2017). Therefore, following on from chapter 5, the final experimental chapter in this thesis (chapter 6) investigated the acute effects of manipulating the order of SSG and resistance training separated by 2 hours of between session recovery time on the performance of training and the 24-hour responses of neuromuscular, endocrine, and mood markers in semi-professional soccer players.

Experimental chapter 6 found that the external load and the RPE for the SSG training sessions were similar between protocols (Table 16; $p > 0.05$), suggesting that the players were able to maintain the physical performance and the intensity of SSG training without an increase in perceived effort when performed 2 hours after resistance training. Whilst SSGs are not a maximal activity and the movement demands depend on many factors discussed previously, this finding may partly corroborate the work of Johnston et al. (2017), who reported that in well-trained athletes, the performance of a maximal speed training session was maintained or possibly even enhanced when undertaken 2 hours after a lower-body strength training session. It should be noted that in the presence of muscle damage, maximal endurance performance (e.g., time to exhaustion and time-trial performance) has been shown to be compromised when undertaken 24 – 48 hours after resistance training (Doma & Deakin, 2013; Doma, Deakin, & Bentley, 2017). However, taking the results of experimental chapters 4 and 6 in this thesis along with those of Johnston et al. (2017), it seems likely that in well-trained athletes, the 2 hours post time point may represent a timeframe after metabolic recovery but prior to the initiation of the inflammatory process, during which the athlete can undertake additional non-exhaustive training without performance being compromised. However, when resistance training was performed 2 hours after SSG training, the RPE for resistance training was significantly higher (7.5 ± 0.8 AU vs 6.6 ± 0.9 AU; $p < 0.05$), although, in agreement with chapter 5, this did not appear to affect the ability to complete the resistance training session as each participant performed the session at the prescribed volume and intensity (i.e., 4 sets of 4 repetitions at 85% 1RM of the barbell back squat, the Romanian deadlift and the hip thrust with 4-min of recovery between sets and exercises). Previous investigations have reported that the ability to maintain resistance training performance or perform repetitions of an exercise until failure is impaired when performed within 30-min of endurance training (Leveritt & Abernethy, 1999; de Souza et al., 2007; Ratamess et al., 2016; Jones et al., 2017). However, the findings of chapter 6 agree with those of Johnston et al. (2017) and Cross et al. (2022) who reported that the total volume and load lifted during a resistance training session remained unaltered when performed 1 and 2 hours after a speed and an intermittent sprint training protocol, respectively. The discrepancy in the literature might be related to the between-session recovery time and the type of resistance exercise performed, and it is possible that when resistance training is performed within 30-min of endurance training this may not be sufficient in mitigating any negative effects of the prior activity. Furthermore, a common feature of previous concurrent training literature is to implement a limited number of resistance training exercises (i.e., one or two) performed until failure (Leveritt & Abernethy, 1999; de Souza et al., 2007), which is not practically representative of a typical in-season resistance training session in team sport athletes (Turner & Stewart, 2014; Silva, Nassis, & Rebelo, 2015; Jones et al., 2016a). Although it is acknowledged that maximum force was not assessed during the resistance training session as this would not have been practically representative of a typical training session and may have exacerbated the fatigue markers, the results of chapter 6 in combination with previous investigations suggest that the appropriate manipulation of training variables in a concurrent training program might somewhat mitigate the negative impact of previous exercise on training performance (Fyfe, Bishop, & Stepto, 2014; Johnston et al., 2017; Cross et al., 2022).

As mentioned above, another primary objective of experimental chapter 6 was to investigate the acute effects of manipulating the training order on the neuromuscular, endocrine and mood responses over 24 hours. Comparisons between the two training sequences revealed that relative PPO was impaired to a greater extent immediately after the first training session during RES+SSG in comparison to SSG+RES (between trial difference; -2.69 ± 3.30 $W \cdot kg^{-1}$; $p < 0.05$; *moderate*). Furthermore, resistance training resulted in a significantly elevated T concentration at 0h during RES+SSG in comparison to the SSG training during SSG+RES (between trial difference; +21.4 ± 26.7 $pg \cdot ml^{-1}$; $p < 0.05$; *moderate*). However, by 24 hours post-training, there were no significant between-protocol differences for any of the neuromuscular, mood, or hormonal measurements taken, suggesting that the order of training may not influence the fatigue and recovery kinetics on the subsequent day. This finding suggests that either order can be scheduled without training performance being further compromised on the following day, and the order of training could be decided by the coach based on other considerations. Current literature suggests that sequencing resistance training prior to endurance training may be beneficial for strength adaptations, with a limited effect on aerobic capacity (Murlasits, Kneffel, & Thalib, 2018). However, whilst this thesis revealed several key findings that may aid practitioners in manipulating training variables to optimise within-day planning, due to the limitations in previous concurrent training literature in its application to applied team sport environments, there is a need for further research into the underpinning mechanisms, the molecular responses, or the longer-term adaptations to manipulating the order of concurrent training in soccer.

7.3 APPLIED IMPLICATIONS

A consistent finding across this thesis is that there was considerable individual variability in the responses to the training sessions. These data are presented in Figures 16 – 21 across the thesis, described within each of the results sections, and interpreted and discussed in sections 4.5.1, 5.5.1, and 6.5.1. Considering that practitioners in elite environments are likely to be monitoring individual athletes in an attempt to identify unusual within- or between-athlete responses, the presentation and interpretation of this data at an individual level may have significant implications for monitoring and adjusting individual training programs.

In agreement with previous literature, the hormonal responses immediately after all the training sessions performed across this thesis were highly variable between individuals, in both the direction and the magnitude of change. For example, broad ranges in the individual percentage changes in T from baseline were evident immediately after the first training session in experimental chapter 4 (-48 – 98%), chapter 5 (single, -20 – 36%; double, -20 – 38%), and chapter 6 (SSG+RES, -20 – 38%; RES+SSG, -20 – 28%). Indeed, previous investigations have reported that changes in T concentration after exercise are highly individual and protocol-dependent (Beaven, Gill, & Cook, 2008; Gaviglio et al., 2015), and there is evidence that there may be 'responders' and 'non-responders', in terms of T secretion, to exercise protocols even of vastly different content (Jensen et al., 1991). Several physiological and psychological factors are thought to potentially modulate the response of the endocrine system to exercise. For example, individual differences in training experience (Kraemer & Ratamess, 2005), baseline strength (Crewther et al., 2012), genetics (Crewther et al., 2009a), nutritional status (Kraemer et al., 1998), social interactions (Archer, 2006), and motivation (Cook, Crewther, & Kilduff, 2013) have all been shown to influence changes in T and C. Nevertheless, there may be an important practical relevance of identifying individual hormonal responses to various activities performed throughout the training week. For example, Beaven, Cook, & Gill (2008) prescribed individual resistance training programs to athletes based on one of four training protocols that elicited the greatest individual T response and reported significantly greater increases in strength (i.e., 1RM leg and bench press) in comparison to programming training based on traditional periodised approach. Furthermore, creating an anabolic hormonal environment could enhance motivation and neuromuscular performance during subsequent training sessions on the same day (Cook et al., 2014; Russell et al., 2016a), later in the training week (Cook, Crewther, & Kilduff, 2013; Cook & Beaven, 2013; Crewther et al., 2016), and there is evidence that this could potentially influence subsequent match outcome (Crewther et al., 2013; Gaviglio & Cook, 2014; Gaviglio et al., 2014).

It is worth noting that there was also considerable individual variability in the hormonal markers at 24 hours post all of the training days assessed through the experimental chapters. For example, relative to baseline, broad ranges of individual percentage changes in the T:C ratio were evident at 24 hours post in chapter 4 (-22 – 158%), chapter 5 (single, -66 – 91%; double, -70 – 71%), and chapter 6 (SSG+RES, -39 – 102%; RES+SSG, -39 – 88%). Recovery from strenuous exercise involves interactions between multiple physiological mechanisms, and hormone signals are part of a complex integrated system that mediates changes in the metabolic and cellular processes of skeletal muscle, neural, and connective tissue as a function of training (Crewther et al., 2011b; Kraemer, Ratamess, & Nindl, 2017). Therefore, previous authors have suggested that hormones should be viewed within the context of the entire endocrine system and its relationship with other physiological variables (Kraemer, Ratamess, & Nindl, 2017). Nevertheless, the chapters across this thesis demonstrate that physically demanding training sessions drive large individual changes in hormone concentrations over a period of just 24 hours in soccer players. However, practitioners would be advised to consider that players should be monitored for meaningful changes over time respective to their normal ranges, and hormonal markers should be used in conjunction with functional markers of neuromuscular performance and perceptual markers of well-being to elucidate a comprehensive understanding of their responses to load.

There were also considerable inter-individual differences in the magnitude of the changes in CK in response to the SSG training session in chapter 4, and the markers of CMJ performance across all the training sessions performed in this thesis. Individual differences in markers of muscle damage and neuromuscular function have also been reported after soccer matches (de Hoyo et al., 2016; Brownstein et al., 2017), which may be related to a number of factors. Previous studies have suggested that the physical and physiological characteristics of a player may influence their response to a given training load (Hunkin, Fahrner, & Gastin, 2014; Johnston et al., 2015b; Owen et al., 2015). For example, previous team sports literature has demonstrated that players with greater aerobic fitness display smaller decrements in RSA (McMahon & Wenger, 1998; Bishop & Spencer, 2004), less pronounced metabolic disturbances following high-intensity activity (Stone & Kilding, 2009), and smaller disturbances in CK throughout a training week (Hunkin, Fahrner, & Gastin, 2014).

Furthermore, it has been suggested that players who possess greater eccentric strength may be more suited to dealing with the high forces during the repetitive SSC activities known to induce fatigue and muscle damage in soccer (Byrne, Twist, & Eston, 2004; Miyaguchi & Demura, 2008). Indeed, Johnston et al. (2015b) reported that rugby league players with better developed physical qualities (i.e., aerobic fitness and lower body strength) have less pronounced post-match declines in CMJ performance and lower CK concentrations, despite producing greater internal and external match loads. Similarly, in elite soccer players, Owen et al. (2015) reported significant relationships between greater lower body strength and lower CK concentrations 48 hours after competitive matches. Whilst exploring these relationships went beyond the scope of this thesis, it is hypothesised that individual differences in physical qualities of the players may have contributed to the fatigue responses observed, and the literature may benefit from future work establishing the influence of the physical qualities and characteristics of the player on the magnitude of fatigue experienced after training sessions in soccer. Furthermore, this provides another justification for the importance of developing lower body strength in soccer and provides further rationale for investigating the interactions between resistance training and on-field training within this thesis. In practice, this might mean that practitioners closely monitor individual players who have been identified as possessing insufficient physical qualities (e.g., aerobic capacity or strength), as these players may be less able to deal with the fluctuations in training load that may occur over a season and require more focused interventions and recovery strategies in subsequent activities performed throughout the week.

Another important factor to consider is that all game scenarios are fundamentally a dynamic interaction between two teams under various contextual factors, therefore, there is an inherent degree of unpredictability in the physical, cognitive, technical, and tactical demands (Gréhaigne, Bouthier, & David, 1997; Clemente, 2019a). Indeed, previous investigations have reported inter-individual variability in the movement demands during both competitive matches (Rampinini et al., 2007b; Gregson et al., 2010) and during SSGs of various formats (Clemente, 2019a; Clemente et al., 2021). Notably, the activities most associated with fatigue in soccer (i.e., high-intensity running and the number of accelerations and decelerations) are typically the most variable metrics (Gregson et al., 2010; Ade, Harley, & Bradley, 2014; Clemente et al., 2019b; Milanović et al., 2020; Younesi et al., 2021). Therefore, it is unsurprising that if the movement demands vary between players, in turn, this may have an impact on the responses observed.

There was also individual variability in the magnitude and direction of the changes in mood scores over this thesis. Indeed, broad ranges in the individual percentage changes in mood score from baseline were evident at 24 hours post-training in chapter 4 (-46 – 120%), chapter 5 (single, -56 – 28%; double, -25 – 60%), and chapter 6 (SSG+RES, -33 – 126%; RES+SSG, -12 – 267%). Considering that the overall mood score was calculated as a composite of ten different questions relating to subjective perceptions of various physical (e.g., muscle soreness, and fatigue), psychological (e.g., anger, confusion, depression, alertness, tension, confidence, and motivation), and lifestyle (e.g., sleep quality) components, it is possible that a plethora of contextual factors may have influenced these individual responses. For example, factors such as perceived individual performance, interactions with teammates and coaches, the result of the SSGs, and external factors outside of the training environment may have had an impact on the individual responses observed. Therefore, in practice, it may be important to isolate or focus on individual questions that may be deviating from normal values and use this to inform specific interventions.

In summary, the individual data reported across this thesis suggests that there may be considerable inter-individual variability in the acute physiological and perceptual responses to training in soccer players. Therefore, practitioners would be advised to consider that there may be a broad range of inter-individual responses even when the content of training is strictly controlled, and large individual changes may be masked when interpreting data at a group level. In practice, this reinforces the importance of monitoring both the activity profiles and the consequential responses of athletes at an individual level and data presented and described within each chapter may give practitioners an insight into the typical ranges of values expected from a comprehensive battery of tests. Furthermore, future applied research in team sport should report individual participant data and investigate the underpinning factors that may contribute to individual variability in response to training sessions.

7.4 LIMITATIONS

There are a number of limitations that pertain to each of the experimental chapters which are important to recognise when interpreting the findings of this thesis. Many of these were due to the applied nature of the research studies and the constraints of collecting data from in-season athletes, however, some components of the studies may have been adjusted if conducting this research again and may need consideration in future research. These are highlighted and discussed below:

- To control the baseline condition of the participants and limit residual fatigue leading into the studies, players were permitted 48 – 72 hours of rest prior to testing. It is recognised that this may be more rest days than elite teams can afford to schedule before undertaking SSG or double training days during the season (Malone et al., 2015a; Owen et al., 2017a). Previous work in soccer has shown that the individual internal training load in the 3 days prior to a match may influence the coaches rating of perceived performance of the players, with higher loads recommended to enhance performance of midfielders and attackers and lower loads for defenders (Rowell et al., 2018). Furthermore, it is well known that match-play results in impairments of neuromuscular function and perturbations in physiological and perceptual markers of fatigue for up to 72 hours (Nedelec et al., 2012; Brownstein et al., 2017; Silva et al., 2018). Therefore, it is possible that if the players had trained or played a match in the days prior to undertaking the training sessions, as is possible in practice, this may have had an impact on both the performance of training and the responses observed. Therefore, practitioners would be advised to consider how the results of the thesis may relate to the scheduling of training in their environment.
- The final time point of data collection in each experimental chapter was at 24 hours post, which in the case of some of our variables was a time point prior to full recovery. This early termination of data collection was due to the reality of the training schedules of the athletes involved in the studies, and it was infeasible to expect the team to refrain from training for another 24 hours when their preparation periods were already time limited. Considering that many studies have reported evidence of fatigue at 48 hours post both soccer match play (Nedelec et al., 2012; Brownstein et al., 2017; Silva et al., 2018) and strength training (Byrne & Eston, 2002; Beneka et al., 2013; Kennedy &

Drake, 2018), obtaining further measurements beyond 24 hours may have been beneficial to establish a full recovery time course in the studies.

- Whilst the assessment of CMJ performance is a practical, valid, and reliable measure of detecting changes in neuromuscular function and correlates with direct neuromuscular measurements after soccer activity (Thomas et al., 2017; Brownstein et al., 2017), information regarding the origin of fatigue (i.e., central vs peripheral) cannot be derived from jumps. This restricted our understanding of the underpinning mechanisms that resulted in the changes in neuromuscular performance throughout this thesis. Furthermore, whilst the CMJ metrics exported for analyses in this thesis (i.e., JH and relative PPO) have been well established as being valid and reliable markers of neuromuscular function and are used extensively in prior research (Cormack, Newton, & McGuigan, 2008; Owen et al., 2014; Johnston et al., 2015a), it is recognised that the analyses of additional CMJ variables (e.g., FT:CT, average power, RFD) may have enhanced our understanding of the neuromuscular response to training. In addition, there is an inherent level of variability associated with all measures of voluntary performance, and previous authors have suggested that proficient jumpers may be able to alter their mechanics under fatigue in an attempt to maximise the height of the jump (Gathercole et al., 2015). Therefore, it is acknowledged that this may have influenced the results and contributed to the individual variability reported across this thesis.
- The participants varied across studies; recruited from a full-time professional team in chapter 4 but a semi-professional team in chapters 5 and 6. This was due to difficulties in scheduling and finding appropriate timeframes to access athletes during the in-season period. Other limitations related to this were that we were unable to carry out a comprehensive fitness testing battery (e.g., maximal aerobic test, RSA performance) for each participant before the commencement of the studies, with the exception of a 3RM strength testing session to determine individual prescribed loads for the strength training exercises in chapters 5 and 6. As discussed within the experimental chapters, it is recognised that the physical qualities of the players may have influenced the magnitude of fatigue experienced, and in turn, the time course of recovery in response to the training sessions across this thesis (Owen et al., 2015; Johnston et al., 2015b).
- During the SSG training, markers of internal load (i.e., HR) were not collected. This was due to alignment with the monitoring strategies of the clubs from which the participants represented at the time of the study, and also the lack of a recent maximal aerobic fitness test highlighted above. Therefore, we were unable to determine a current

max HR for each participant, limiting our ability to report HR markers such as the percentage of time spent in various HR zones. This may have broadened our understanding of the demands of the SSG training sessions, although there is already an abundance of research in this area (reviewed in section 2.3.2).

- The HSR threshold (i.e., ≥19.8 km.h^{-1}) applied across the chapters in this thesis was selected as it is very common in previous soccer literature (e.g., Thorpe & Sunderland, 2012; Gaudino et al., 2013; Lacome et al., 2018), reported at elite clubs (Akenhead & Nassis, 2016), and matched the monitoring strategies of the teams recruited from at the time of study. However, it is acknowledged that it is high for the SSG format (i.e., 4 vs 4 +GKs) and the pitch size used (width x length; 24 x 29 m). This is likely to have inhibited the players ability to fully accelerate to the required velocity to register as a high-intensity effort. Therefore, the capture and analyses of running distances at lower speed thresholds may have been more appropriate for the SSG format used and given a more comprehensive picture of the physical demands during training.
- Comparable thresholds for high-intensity acceleration and deceleration metrics were unavailable to export for analyses from the SSG training sessions across this thesis. It is recognised that these are likely to have been important metrics to monitor during SSG training due to the distinct physiological and mechanical stresses applied to players during these activities (Hodgson, Akenhead, & Thomas, 2014; Lacome et al., 2018; Harper, Carling, & Kiely, 2019). Indeed, the number of high-intensity accelerations and decelerations performed during soccer matches has been associated with post-match reductions in neuromuscular and indicators of muscle damage (Nedelec et al., 2014; de Hoyo et al., 2016; Hader et al., 2019). It is recognised that measuring both the quantity and the magnitude of these events is likely to have provided a greater understanding of the physical demands of the SGG training and the activities that were driving the physiological and perceptual responses.
- Blood samples were drawn in chapter 4 to quantify BLa and CK concentrations, however, no blood samples were drawn in chapters 5 and 6 due to logistical constraints. It is recognised that the consistent collection of these markers across every chapter may have been useful in understanding the responses to the training sessions and also facilitated a better comparison between the studies.
- Due to the logistical constraints of collecting multiple measurements from a squad of players in a short time frame, there would have inevitably been slight differences between the proximity of each participants assessment to the cessation of exercise. This

pertains to both the end of the training sessions and the pre-jump warm up. We strived to counteract this by ensuring adequate equipment and personnel were available to ensure a smooth flow of data collection, however, it is possible that if a participant had their assessments performed closer or further away from exercise cessation, this could have had an impact on the responses observed. However, it should be noted that this limitation is not unique to the studies in this thesis. For example, previous studies have obtained neuromuscular measurements at 40-min (Rampinini et al., 2011) and between 10 – 60 minutes (Brownstein et al., 2017) post soccer matches, and still reported significant impairments in performance. Furthermore, Brownstein et al. (2017) found no significant relationship between the proximity of post-match neuromuscular assessments to the end of a match and the magnitude of muscle fatigue experienced.

- All the warm-ups prior to SSG training across the experimental chapters in this thesis were standardised, consisting of 5-min of mobility exercises, dynamic stretching, and short sprints. However, it is acknowledged that the on-field warm-up prior to SSG training was short (i.e., 5-min) in comparison to previous recommendations of 12 – 16-min prior to soccer (Zois et al., 2011; McGowan et al., 2015). It is possible that in this period, not all the proposed mechanisms of warm-up were fully elicited (e.g., increased blood flow, decreased stiffness, increased nerve conduction rate, increased oxygen delivery to muscles, increased rate of metabolic reactions, psychological preparedness, enhanced VO2 kinetics, and PAP) (Bishop, 2003a). Whilst it has been reported that a warm-up of 3 – 5 min is effective in raising muscle temperature and enhancing vertical jump performance (Bishop, 2003b), it is possible that a longer warm-up may have fully realised all of the proposed mechanisms of warm-up and enhanced training performance.
- The training sessions across this thesis were subjectively performed in temperate environments, however, the non-measurement of direct environmental conditions is a limitation. Research suggests that soccer players may modify their physical activity patterns to suit the environmental conditions and maintain key physiological parameters that are critical to match performance (Nassis et al., 2015; Slattery & Coutts, 2019). Furthermore, heat stress can negatively affect many aspects of team sport performance, including aerobic capacity (Mohr et al., 2012), cognitive ability (Bandelow et al., 2010), perception of effort (Duffield, Coutts, & Quinn, 2009), and the ability to perform repeat sprints (Girard, Brocherie, & Bishop, 2015), likely due to increased thermoregulatory strain and dehydration (Slattery & Coutts, 2019). Therefore, it is possible that

undertaking training under different environmental conditions may influence the performance of training and subsequent physiological responses.

- Participants recruited within the studies were instructed to follow their usual dietary routines in the days leading up to and during the studies and were provided with food and water at the training facilities. However, there were no diet records kept or monitoring of hydration status, which is a limitation of the studies in this thesis. It is well known that adequate carbohydrate consumption is vital for sporting performance, and indeed, muscle glycogen is suggested to be the predominant substrate for energy provision during soccer performance, as well as being essential for post-exercise muscle and liver glycogen resynthesis (Oliveira et al., 2017). Furthermore, adequate protein intake (e.g., 1.2 – 2 g/kg/day) is imperative to facilitate protein synthesis and promote recovery after exercise (Thomas, Erdman, & Burke, 2016). Observational studies suggest that soccer players generally meet daily requirements for protein intake, but perhaps not for carbohydrates (Briggs et al., 2015; Bettonviel et al., 2016; Naughton et al., 2016; Devlin et al., 2017). Furthermore, some percentage of dehydration commonly occurs in soccer, and a significant amount of fluid can be lost through sweating even when a match is played in a cold weather environment (Oliveira et al., 2017). However, considering that total SSG playing time was 42-min with 2-min breaks given between repetitions where players were allowed to drink water *ad libitum*, and food was provided, it seems unlikely that inadequate energy intake and hydration had a significant impact on performance and recovery in this thesis. However, with a lack of strict control of the quantities consumed or recording of this, it cannot be discounted.
- Finally, as with many applied studies in team sports, there were relatively low participant numbers (n = 12 – 16). Consequentially, we were unable to randomise the order of trials in chapters 5 and 6 to ensure enough players were available for the coaches to carry out the SSG training sessions.

7.5 PRACTICAL APPLICATIONS OF RESEARCH FINDINGS

There are a number of practical applications that can be taken from this thesis that may aid practitioners (e.g., coaches, sports scientists, strength and conditioning coaches, and physical performance staff) to optimise soccer training:

- The external demands during SSG training (6x7-min; 2-min recovery) may decline across repetitions, whereby the first repetition is of a significantly higher intensity than the following repetitions. This may be favourable if looking to mimic the demands of match performance, however a strategy of allowing longer rest periods (i.e., ≥2-min) may maintain the intensity across repetitions.
- Performance of SSGs results in impairments of CMJ performance, disturbances in mood, hormones, and evidence of muscle damage in the 24 hours that follow. Therefore, this should be considered when determining their placement within a program, given the possible influence this may have on additional training activities performed throughout the week.
- Considering the bimodal recovery of neuromuscular function observed in response to SSG training, the 2-hour post time point may represent a superior window for further intense training than immediately or at 24 hours post. Coaches would be advised to take advantage of this when sequencing or programming training.
- However, the addition of a lower body strength training session 2 hours after SSG training results in further *small* disturbances in neuromuscular performance, mood, and endocrine markers 24 hours later. This suggests that training performance on the day after a double training day may be further compromised, and a reduced training load may be beneficial on this day.
- Performance of submaximal activities may be unaffected at 24 hours post either SSG training alone or a day combining SSG and resistance training. Therefore, a strategy of alternating high-intensity explosive training days containing multiple sessions, with days emphasising submaximal technical and tactical activities may be beneficial.
- Manipulating the order of SSG and resistance training with 2 hours of between-session recovery time does not significantly influence neuromuscular, endocrine or mood responses 24 hours later. This suggests that either sequence can be scheduled without

recovery being further compromised and could be decided by the coach based on other considerations.

- The order of SSG and resistance training sessions with sufficient between-session recovery time (e.g., ≥2 hours) does not appear to influence the perceived effort or the external demands during SSG training. However, when resistance training is performed 2 hours after SSGs, the perceived effort is higher, but the ability to complete the training session as prescribed is maintained.
- Analyses of individual participant data across this thesis revealed that there may be highly individual responses to training which may be masked when analysing data at a group level. Therefore, practitioners would be advised to consider this when implementing monitoring strategies and apply methods that are able to identify unusual within- and between-athlete responses to training. This may require consideration for prescribing individual training loads in subsequent activities or training sessions.
- Finally, the presentation and interpretation of data at an individual level in this thesis provides practitioners with a potential range of values that may be expected from a comprehensive battery of tests.

Appendices

Appendix 1:
Participant Information Forms

Applied Sports Technology Exercise and Medicine Research Centre (A-STEM)
Sport and Health Portfolio, College of Engineering

PARTICIPANT INFORMATION SHEET
(Version 1.1, Date: 04/12/2017)

Project Title:
The physiological responses to concurrent training in soccer players

Contact Details:

Will Sparkes
Email: [redacted]
Mobile: [redacted]

1. Invitation Paragraph
You have been invited to take part in a study involving a series of measures to see how your body is responding to your training sessions. The measures include a saliva sample, countermovement jumps on a FP, and a questionnaire to assess your mood state in relation to sport. You will also be monitored using a GPS device during training.

2. What is the purpose of the study?
The purpose of this study is to assess how your body are responding to your various training sessions (strength and on-field). Once this has been established, we will aim to discover how long is required to recover from a single vs double session, and also the effects of the sequencing of training your subsequent performance.

3. Why have I been chosen?
You have been identified as a potential participant as you are a considered to be a Football player who is competing at a high enough level to participate. You have the right to withdraw from this study at any point and participation is entirely voluntary.

4. What will happen to me if I take part?
We will be monitoring your physical condition via a number of measures on the day of training and on the following day. You will be asked to provide saliva samples, fill in questionnaires and perform jumps on a FP. In addition to this, you will be asked to carry out lower-body strength training exercises, as well as complete on-field sessions (small-sided games). At times, both pitch and gym sessions will be completed on the same day.

5. What are the possible disadvantages of taking part?

The main risk of participating in this study is injury. However, there is no additional risk that you will experience compared to your normal training sessions and schedules.

6. What are the possible benefits of taking part?

Taking part in this study will provide information how you are responding to training sessions. This will improve our knowledge on how to best program the week so that you improve as players.

7. Will my taking part in the study be kept confidential?

Information collected will be kept confidential with a numerical format of results to prevent participant identification. The data will be stored on a password-protected computer and will only be accessed by the team of researchers. A Journal could publish the final research paper, which would include data and analysis of results. This would remain online for future researchers.

8. What if I have any questions?

I am more than happy to answer any questions you may have about the study. Please use the contact details above to get in touch.

Appendix 2:
Participant Consent Forms

Applied Sports Technology Exercise and Medicine Research Centre (A-STEM)
Sport and Health Portfolio, College of Engineering

PARTICIPANT CONSENT FORM
(Version 1.1, Date: 04/12/2017)

Project Title:

The physiological responses to concurrent training in soccer players

Contact Details:

Will Sparkes
Email: [redacted]
Mobile: [redacted]

Please initial box

1. I confirm that I have read and understood the information sheet dated ....../....../...... (version number ....) for the above study and have had the opportunity to ask questions. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected. ☐
3. I understand that sections of any of data obtained may be looked at by responsible individuals from the Swansea University or from regulatory authorities where it is relevant to my taking part in research. I give permission for these individuals to have access to these records. ☐
4. I agree to take part in the above study.

____________________	____________	____________________
Name of Participant	Date	Signature
Name of Person taking consent	Date	Signature
Researcher	Date	Signature

AHA/ACSM Health/Fitness Facility Pre-participation Screening Questionnaire.

Name: ………………………………………………………..……………………
Address: ……………………………………………………………………………..
……………………………………………………………………………..
Tel. Number: ……………………………………………….
Emergency Contact Name: ……………………………….. Tel No.: ……….…………….

Assess your health needs by marking all *true* statements.

History
You have had:
- a Heart Attack;
- Heart Surgery;
- Cardiac Catheterization;
- Coronary Angioplasty (PTCA);
- Pacemaker/implantable cardiac defibrillator/rhythm disturbance;
- Heart valve disease;
- Heart failure;
- Heart transplantation;
- Congenital heart disease.

If you marked any of the statements in this section, consult your healthcare provider before engaging in exercise. You may need to use a facility with a ***medically qualified staff****.*

Cardiovascular risk factors
- You are a man older than 45 years.
- You are a woman older than 55 years or you have had a hysterectomy or you are post-menopausal.
- You smoke.
- Your blood pressure is greater than 140/90.
- You don't know your blood pressure.
- You take blood pressure medication.
- Your blood cholesterol level is >240 mg/dL.
- You don't know your cholesterol level.
- You have a close blood relative who had a heart attack before age 55 (father or brother) or age 65 (mother or sister).
- You are diabetic or take medicine to control your blood sugar.
- You are physically inactive (i.e., you get less than 30 minutes of physical activity on at least 3 days per week).
- You are more than 20 pounds overweight.

Symptoms **and other health issues:**
- You experience chest discomfort with exertion.
- You experience unreasonable breathlessness.
- You experience dizziness, fainting, blackouts.
- You take heart medications.
- You have musculoskeletal problems.
- You have concerns about the safety of exercise.
- You are pregnant.
- You take prescription medication(s).

If you marked two or more of the statements in this section, you should consult your healthcare provider before engaging in exercise. You might benefit by using a facility with a ***professionally qualified exercise staff*** *to guide your exercise program.*

- **None of the above is true**.

You should be able to exercise safely without consulting your healthcare provider in almost any facility that meets your exercise program needs.

Appendix 3:
Ethical Approval Forms

Applied Sports Technology Exercise and Medicine Research Centre (A-STEM)
Sport and Health Portfolio, College of Engineering

Swansea University
Prifysgol Abertawe

APPLICATION FOR ETHICAL COMMITTEE APPROVAL OF A RESEARCH PROJECT

In accordance with A-STEM and College of Engineering Safety Policy, all research undertaken by staff or students linked with A-STEM must be approved by the A-STEM Ethical Committee.

RESEARCH MAY ONLY COMMENCE ONCE ETHICAL APPROVAL HAS BEEN OBTAINED

The researcher(s) should complete the form in consultation with the project supervisor. After completing and signing the form students should ask their supervisor to sign it. The form should be submitted electronically to Prof Mike McNamee [redacted]) and Dr Melitta McNarry ([redacted].

Applicants will be informed of the Committee's decision via email to the project leader/supervisor.

1. TITLE OF PROJECT

The Neuromuscular, biochemical and endocrine responses to training in professional soccer players

2. DATE OF PROJECT COMMENCEMENT AND PROPOSED DURATION OF THE STUDY

The project will begin October 2016 and will be completed by December 2021.

3. NAMES AND STATUS OF RESEARCH TEAM

Will Sparkes (Postgraduate, Swansea University)
Professor Liam Kilduff (Supervisor, Swansea University)
Dr Michael Johnston (UK Athletics)
Dr Matthew Weston (Teeside University)
Dr Mark Russell (Northumbria University)

4. RATIONALE AND REFERENCES

Team sport athletes are required to train multiple physical qualities concurrently, with various methods of proposed training periodisation suggested (Issurin, 2010; Prestes et al, 2009). Regardless of the method utilized, to achieve the required physical adaptations it is often necessary for several different training sessions to be performed within close proximity to each other (Hakkinen, 1992; Hakkinen & Kallinen, 1994; Hartman, et al, 2007).

Soccer is an intermittent sport which involves periods of high-intensity activity (sprinting, changes of direction, jumping, kicking and tackling), interspersed with lower intensity actions (jogging, walking and standing), as well as technical and tactical components (Bangsbo, 1994). Due to the multifaceted game demands, soccer players are likely to train a number of physical qualities, including but not limited to; strength, power, speed, agility, aerobic capacity, repeated sprint ability, as well as technical and tactical training (Reilly and Rigby, 2002). Whilst the fatigue response from soccer matches has been well documented (Russell et al, 2016; Nedelec et al., 2012), to date little is known about the fatigue response from a single soccer training session, or the combined effects of multiple sessions. For the athletes to positively adapt to training, the stimulus should be applied in an order or a spacing that allows recovery to a point where they are able to meet the demands of the following training session (Bishop, Jones, & Woods, 2008). A greater understanding of the fatigue response accumulated from soccer training sessions, as well as the combined effects of multiple training sessions will allow better design of soccer training programs.

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Reilly, T., & Rigby, M. 2002. Effect on active warm-down following competitive soccer. In: W.Spinks, T.Reilly, A.Murphy (eds.) *Science and Football IV*; pp.226-229.

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5. OBJECTIVES

This primary aim of this project is to characterise the neuromuscular, endocrine, movement, biochemical and mood responses to professional soccer training.

Secondary objectives:

- To quantify the fatigue response of a single soccer training session (i.e., small-sided games).
- To compare the response to a training day consisting of solely a soccer session to one consisting of a soccer training session plus a strength training session.
- To investigate the effects of varying soccer and strength training session order on fatigue response over a 24 h period.

6.1 STUDY DESIGN

The responses to various training sessions will be examined using a number of measures. Neuromuscular performance will be assessed using FPs via a countermovement jump (CMJ). Blood samples will be obtained via a fingertip puncture using a spring loaded disposable lancet. The endocrine response will be analysed from a salivary sample. Players will provide a brief assessment of their mood in relation to their sport through filling out 10 questions on an electronic tablet. Additionally, athletes will be required to give ratings of perceived exertion (RPE) on each training session completed. Time-motion analysis data will be collected using GPS units attached to the upper back of players using a custom vest.

6.2 STUDY DESIGN

Participants will be male professional soccer players (aged between 18 - 30 years) from the English Premier League that represent Swansea City AFC. The inclusion criterion consists of physically healthy males who train at a professional level. In terms of the exclusion criterion, they must not have any injuries that could affect the data collection, this will be assessed by the Clubs medical staff. The participants must perform to the best of their ability on each test and during each training session. They will be required to perform normal soccer specific activities as well as carry out strength training sessions as normally supervised and prescribed by their coaches.

6.3 PARTICIPANT RECRUITMENT

Participants will be male professional soccer players (aged between 18 -30 years) who represent Swansea City football club. Any player who has been selected to train with the under 23 squad on the day of testing will be involved in the study, providing they have provided consent and read and understood the participant information sheet.

6.4 DATA COLLECTION METHODS

Before the participants take part in the practical experiment, they shall be given a Participant Information Sheet (APPENDIX A) to be read and understood. They will also be given an ACA/ACSM Health Screening Questionnaire (APPENDIX C) and a Participant Consent Form (APPENDIX B) to be filled out. All data will be collected at the Swansea City FC Training ground.

All data collection will commence after players have been given two days off prior, in order to ensure that players are at a non-fatigued state. On arrival at the training ground (8:45 am) and pre breakfast, players will perform their baseline testing measures. These include providing a saliva sample, filling out an electronic questionnaire, blood capillary sampling and countermovement jump (CMJ) testing. At approximately 10:30 am, players will report to train. This will either be a field-based training session (SSGs) or a gym based training session (Strength), or a combination of both. Immediately post training (approximately 11:30 am), players will be escorted to the gym for a repeat of the testing procedures (blood, CMJ, saliva and questionnaire) as well as provide differential RPE scores. Players will then consume lunch on site and refrain from any physical activity. Another repeat of the measures (blood, CMJ, saliva and questionnaire) will be carried out at 2 hours after the end of the training session (approximately 13:30 am). Another follow up (blood, CMJ, saliva and questionnaire) will be taken on the following morning (+ 24 hours) at 8:45 am.

Small Sided Games

After completion of a standardized warm-up, players will be split into 4 teams of 5 by their coaching staff. The teams will be organised so that there is an even number of playing positions in each team (e.g 1 goalkeeper, 1 defender, 1 winger, 1 midfielder, 1 striker). On instructions from their coaches, teams will play against another team for 6 blocks of 7 minutes (42 minutes overall). Players will be given 2 minutes between each block in order to drink water and rest. Pitch size will be the same as their typical coaching session staff (29 meters in length and 24 meters in width), as advised by the coaching staff, and with full-sized goals in place. Coaches will keep scores throughout the completion of all 7 games, so that the games remain competitive.

Strength Training

The exercise choice, volumes and intensities will reflect those used by the participants in their normal lower body strength training sessions, whilst also being in line with the guidelines for the development of strength outlined in the literature. The session will consist of five sets of four repetitions of the parallel back squat and five sets of four repetitions of the Romanian dead lift, all at 85% of current 1RM and with four minutes' recovery between sets. Each exercise will be preceded by two sets of four at 50% and 70% 1RM by way of a warm-up. Participants are regularly tested on their 1RM data. The session will be supervised by a United Kingdom Strength and Conditioning Association (UKSCA) accredited strength and conditioning coach to ensure appropriate technique is maintained throughout.

Countermovement Jump (CMJ) Testing

A portable FP (Type 92866AA, Kistler) will be used to measure neuromuscular performance of the lower body. This will entail countermovement jumps (CMJ), performed at maximum effort with arms akimbo to isolate the lower body. All jumps will be completed after a standardized warm-up.

The data will be used to calculate peak power output from the vertical ground reaction forces recorded.

Saliva Testing
A 2ml sample of saliva will be collected at all time points via a passive drool into a sterile container. These will be stored at a temperature of -20° C until analysis. Post thawing and centrifugation (2000 rpm x 10 minutes), saliva samples will be analysed for testosterone and cortisol concentrations using commercial kits (Salimetrics LLC, USA).

Blood Plasma Testing
Whole blood will be collected via a fingertip puncture using a spring loaded disposable lancet (Safe-T-Pro Plus, Accu-Chek, Roche Diagnostics GmBH, Germany). A 120-µL sample will be collected in a capillary tube and centrifuged (Labofuge 400R, Kendro Laboratories, Germany) at 3000 rpm for 10 minutes to extract the plasma. This will then be stored at -20° C before thawing and analysis for Creatine Kinase (CK) and IL-6 concentration.

Mood Assessment
Mood state will be assessed using a modified brief assessment of mood (BAM) questionnaire. The questionnaire will be carried out electronically via an Ipad. This 10-item questionnaire is based on the Profile of Mood State assessment (McNair et al., 1971) and consists of a scale where players mark how they feel at that moment of time. The questions assess the following mood adjectives: anger, confusion, depression, fatigue, tension, alertness, confidence, muscle soreness, motivation and sleep quality. If the questionnaire returns negative findings and it is deemed as a risk for players to continue with further training, players will be referred to the club's medical staff and information will be passed onto the coaching team.

Differential RPE
Using the centiMax scale, players will be asked to differentiate between local (e.g. legs) and central (e.g. breathlessness) ratings of exertion. Players will also use this scale to provide ratings of overall match physical exertion), and overall match technical demand). Recent research has demonstrated the CR100 scale possesses good construct validity in AFL.

Time-motion Analysis
Time-motion data will be collected via 10 Hz global positioning units (Catapult Sports) worn by the players during all on-field training sessions. The data will be downloaded from the units and analysed using Catapult Sports software.

6.5 DATA ANALYSIS TECHNIQUES

A repeated measures ANOVA will be the statistical test used with SPSS software. This will determine whether there are any significant effects of training across time. A correlation matrix will also be used to examine relationships between training load metrics and markers of neuromuscular fatigue and muscle damage. Data will be represented as mean ± SD and presented on graphs and in tables generated using Microsoft Excel.

6.6 STORAGE AND DISPOSAL OF DATA AND SAMPLES

Data will be presented anonymously in a numerical format, original list of names and assigned numerical codes and will be stored on a password protected, secure computer at Swansea University with only the research team mentioned in section 3 and Swansea City FC staff gaining access. Excel files will also be password protected to add an additional level of security. Data will be deleted on award of degree.

6.7 HOW DO YOU PROPOSE TO ENSURE PARTICIPANT CONFIDENTIALITY AND ANONYMITY?

The data collected will be stored in a numerical format to avoid participant identification.

7. LOCATION OF THE PREMISES WHERE THE RESEARCH WILL BE CONDUCTED.

The study will take place at Swansea City football club's training facility. Professor Liam Kilduff is the primary supervisor who will be present throughout the entire data collection. A qualified first aider and physiotherapist (Huw Roberts) will be on hand during training and data collection.

8. POTENTIAL PARTICIPANT RISKS AND DISCOMFORTS

The potential discomforts that may concern participants are the withdrawal of blood capillary samples and production of maximum power through a CMJ. As participants will be expected to carry out normal training commitments, there is a risk of muscle soreness and potential injuries. However, this is an intrinsic rick of the game and not from the testing or collection procedures. There will be the standard medical cover during training sessions from physiotherapists and doctors. Athletes will be fully debriefed afterward and can receive external feedback throughout.

9.1 HOW WILL INFORMED CONSENT BE SOUGHT?

Swansea City Football Club will be the organisation used to access the sample population. Coach consent will be required and will be obtained through regular contact with the main coaches before the study commences. This will be recorded through email. Consent from each individual player prior to testing will also be obtained.

9.2 INFORMATION SHEETS AND CONSENT/ASSENT FORMS

- Have you included a Participant Information Sheet for the participants of the study? YES
- Have you included a Parental/Guardian Information Sheet for the parents/guardians of the study? NO
- Have you included a Participant Consent (or Assent) Form for the participants of the study? YES
- Have you included a Parental/guardian Consent Form for the participants of the study? NO

10. IF YOUR PROPOSED RESEARCH IS WITH VULNERABLE POPULATIONS (E.G. CHILDREN, PEOPLE WITH A DISABILITY), HAS AN UP-TO-DATE DISCLOSURE AND BARRING SERVICE (DBS) CEHCK (PREVIOUSLY CRB) IF UK, OR EQUIVALENT NON-UK, CLEARANCE BEEN REQUESTED AND/OR OBTAINED FOR ALL RESEARCHERS? EVIDENCE OF THIS WILL BE REQUIRED.

N/A

11. STUDENT DECLARATION

Please read the following declarations carefully and provide details below of any ways in which your project deviates from these. Having done this, each student listed in section 2 is required to sign where indicated.

- ***"I have ensured that there will be no active deception of participants.***
- ***I have ensured that no data will be personally identifiable.***
- ***I have ensured that no participant should suffer any undue physical or psychological discomfort (unless specified and justified in methodology).***
- ***I certify that there will be no administration of potentially harmful drugs, medicines or foodstuffs.***
- ***I will obtain written permission from an appropriate authority before recruiting members of any outside institution as participants.***
- ***I certify that the participants will not experience any potentially unpleasant stimulation or deprivation.***
- ***I certify that any ethical considerations raised by this proposal have been discussed in detail with my supervisor.***
- ***I certify that the above statements are true with the following exception(s):"***

Student/Researcher signature: (include a signature for each student in research team)

[redacted]

Date: 06/09/2016

12. SUPERVISOR'S APPROVAL

Supervisor's signature:

Date:

Appendix 4:
Mood Questionnaire

NAME: DATE/ TIME:

Below are 10 questions we would like you to answer concerning how you feel. These questions are answered by indicating your feelings on a continuous line that ranges from 'not at all' to 'extremely.' Please read each one carefully then put a vertical line along the line that best describes HOW YOU FEEL RIGHT NOW in relation to your sport. Make sure you answer every question.

E.g. Not at all ——|—— Extremely

1. How angry do you feel? Not at all —— Extremely

2. How confused do you feel? Not at all —— Extremely

3. How depressed do you feel? Not at all —— Extremely

4. How fatigued do you feel? Not at all —— Extremely

5. How tense do you feel? Not at all —— Extremely

6. How alert do you feel? Not at all —— Extremely

7. How confident do you feel? Not at all —— Extremely

8. How sore do your muscles feel? Not at all —— Extremely

9. How motivated to train do you feel? Not at all —— Extremely

10. How well do you feel you have slept? Not at all —— Extremely

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