NEUROMUSCULAR RESPONSE TO MATCH LOAD IN FEMALE YOUTH SOCCER WITH CONSIDERATION TO UNLIMITED SUBSTITUTIONS

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Abstract

The aim of this thesis was to examine the neuromuscular response to match-play in female adolescent soccer with consideration to unlimited substitutions. Previous studies of female adolescent match-play have not included analysis of substitution match loads and previous studies of neuromuscular response in adolescent female soccer players have been limited to simulated match-play. This thesis assessed sprint-speed ability in adolescent female soccer players to determine an appropriate sprint-speed threshold to analyse sprint-speed movement during match-play, analysed match load for full-match and substitute players across several matches, and examined neuromuscular responses to match-play using exercise performance tests.

In Study 1 (Chapter 4), two methods of data collection — timing gates (SmartSpeed PRO system timing gates, Fusion Sport, Queensland, Australia) and a global positioning system (GPS; GPSports HPU system, Canberra, Australia) — were used to assess sprint speed in a cohort of 64 high-level U16 female players, over a short, match-specific sprint distance of 20 m and a maximal effort run over a longer distance. Previous studies have shown that sprint speed increases with age until a plateau around 15 or 16 years with smaller increases in sprint speed into adulthood (Vescovi et al., 2011). Determining an appropriate sprint-speed threshold for female players under the age of 16 was of importance prior to assessing match-play. Both sprint tests were determined to be reliable with reproducible results (between-session ICC for MEAN: > 0.80; CV < 5%). Mean speed in the flying 10 m sprint split measured via timing gates was 6.96 ± 0.35 $m \cdot s^{-1}$. Mean maximal sprint speed assessed via GPS in the maximal effort run over a >30 m distance was 7.25 ± 0.33 $m \cdot s^{-1}$. Utilising 80 – 85% of flying 10 m split sprint speed (Bradley & Vescovi, 2015) yielded a sprint-speed threshold of 5.57 – 5.92 $m \cdot s^{-1}$, which aligns closely with the previously utilised

$5.56\ m{\cdot}s^{-1}$ threshold determined from adult female soccer player sprint speeds (Bradley & Vescovi, 2015; Ramos et al., 2019; Vescovi, 2014). This study found that the sprint-speed threshold previously utilised for female adolescent match-play analysis could be used for match analysis of players ≥14 years of age.

In Study 2 (Chapter 5) of this thesis, GPS was used to track player movement during match-play to determine match load for 36 players in two U16 teams over 20 matches during the regular season. Positional differences, differences between full-match and substitute match loads, and differences in match load between 1st and 2nd match halves were assessed. The established sprint-speed threshold was used to assess sprint-speed efforts during match-play in addition to accelerations and deceleration calculated from speed data determined with the GPS. Match loads were affected by position, with Forward players completing higher sprint-speed distances (F: 219.0 m > M: 123.5 m & D: 153.3 m) and more sprint speed efforts (F: 13 > M: 8 & D: 9), and Midfield players observed to have higher total distances (M: 8388.8 m > F: 7801.8 m & D: 7601.5 m), work rates (M: $105.1\ m{\cdot}min^{-1}$ > F: $97.5\ m{\cdot}min^{-1}$ & D: $95.2\ m{\cdot}min^{-1}$), and low-speed distances (M: 7750.2 m > F: 6939.3 m & D: 6944.0 m). These between-position differences were similarly observed in substitution conditions. Within-position differences between full-match and substitute players did not reveal significant differences for Forward players. Midfield and Defender substitute players had significantly higher work rates, relative high-speed running distances, and relative acceleration and deceleration counts compared to full-match Midfield and Defender players. Examination of between-half differences in match load revealed significant decreases in total distance, low-speed running distance, average speed, and deceleration counts for all positions and significantly decreased acceleration counts into the 2nd half for Midfield and Defender players. Sprint-speed running distances were not observed to decrease between match halves.

Further, between-half decreases were largely absent for Forward and Defender substitutes, but not for Midfield substitute players. The study provides coaches and support staff with new information about the match loads of substitute players in consideration of unlimited substitutions in youth soccer. Acceleration and deceleration counts may provide more reliable tracking of performance decline during match-play compared to speed-based analysis. Substitution match loads and positional differences highlighted in the study also provide further information to inform training programming to enhance player development.

In Study 3 (Chapter 6), 211 player-sessions were collected with 36 participants over 20 matches including match load and results of three exercise performance tests for neuromuscular response (NMR). Tests were performed pre- and post-match to assess NMR to match-play, including a countermovement jump (CMJ) test, maximal hop test for reactive strength index (RSI), and submaximal hop test for relative leg stiffness. The effects of position, substitution, chronological age, and maturation on NMR were assessed, in addition to effects of match load on NMR. The maximal hop test for RSI was not found to be a useful tool to assess NMR in the current study. Maturation and chronological age effects were observed, with pre- to post-match CMJ height significantly decreased in the Year 2 and Mat 2 groups but maintained CMJ height in Year 1 and Mat 1 groups. In analysis of relationships between match load and NMR, deceleration was found to be negatively correlated with pre- to post-match CMJ response. This negative correlation with CMJ response was present in analysis of full-match, but not substitute conditions, where full-match players recorded higher total deceleration counts as determined in Study 2. Overall, relative leg stiffness was found to decrease from pre- to post-match and was not different between positions. Significantly increased contact time and significantly decreased flight time to calculate leg stiffness were observed in full-match conditions; these significant differences were not observed in

substitution conditions. Positive relative leg stiffness responses were also observed for some individual player-sessions. Magnitude-based inferences also revealed variations in NMR per team per match, reflecting individual differences in NMR. Negative NMR in CMJ tests and changes to relative leg stiffness represent altered neuromuscular control to the lower limb and may be considered indicators of fatigue and increased injury risk in response to match-play which coaches and support staff should be aware of in efforts to prevent injury.

Together, the data presented in this thesis provide new information for understanding the match loads of substitute players, further knowledge of positional differences in match loads, and new understanding of neuromuscular responses to match-play in female adolescent soccer. Reliable methods to determine sprint speed utilising GPS over different distances provide further performance assessment tools for coaches. Match loads described in the current work provide data for the development of position- and substitution-specific training, especially with regards to high-speed and high-intensity movement including sprint-speed efforts and accelerations and decelerations. Further, the data provide important information for use of substitutions to mitigate performance decrements during match-play. Neuromuscular response data provide indications of fatigue development due to match-play that should be considered to inform recovery and injury prevention in female adolescent soccer.

Declaration

I declare that the work in this thesis was carried out in accordance with the regulations of the University of Gloucestershire and is original except where indicated by specific reference in the text. No part of the thesis has been submitted as part of any other academic award. The thesis has not been presented to any other education institution in the United Kingdom or overseas.

Any views expressed in the thesis are those of the author and in no way represent those of the University.

Signed

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negative; L-N = likely negative; VL-N = very likely negative; ML-N = most likely negative; P-P possibly positive; L-P = likely positive; VL-P = very likely positive.

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List of Abbreviations

ACCEL	Acceleration count
ACL	Anterior cruciate ligament
AVG	Average speed
BEST	Best of 3 trials
bpm	Beats per minute
CK	Creatine kinase
cm	Centimetres
CMJ	Countermovement jump
CNS	Central nervous system
Ct	Contact time
CV	Coefficient of variation
D	Defender
DECEL	Deceleration count
EMD	Electromechanical delay
ES	Effect size
F	Forward
FA	The Football Association
Ft	Flight time
FULL	Full-match
GDPR	General Data Protection Regulation
GPS	Global positioning system
GPSmax	Maximal speed measured via GPS
h	Hours
H	Hamstring

HIA	High-intensity acceleration
HR	Heart rate
HR_{max}	Maximal heart rate
HSA	High-speed activity
HSE	High-speed effort
HSR	High-speed running
Hz	Hertz
ICC	Intraclass correlation coefficient
JH	Jump height
kg	Kilogrammes
$km \cdot h^{-1}$	Kilometres per hour
LOW	Low-speed running distance
m	Metres
M	Midfield
$m \cdot s^{-2}$	Metres per second squared
$m \cdot min^{-1}$	Metres per minute
$m \cdot s^{-1}$	Metres per second
MEAN	Mean of 3 trials
MER	Maximal effort run
min	Minutes
MSS	Maximal sprint speed
NCAA	National Collegiate Athletic Association
NMF	Neuromuscular fatigue
NMRT	Neuromuscular response test
PHV	Peak height velocity

Q	Quadricep
Rel-	Relative measure
REPEAT	Repeat sprint
reps	Repetitions
RR	Relative risk ratio
RS	Repeated sprints
RSA	Repeated sprint ability
RSI	Reactive strength index
RTC	Regional Talent Club
s	Seconds
$SAFT^{90}$	Soccer-specific aerobic field test
SPR	Sprint-speed running
SSC	Stretch-shortening cycle
SUB	Substitute
SUBrest	Substitution condition with extended rest
TG	Timing gate
TGmax	Maximal speed measured via timing gates
TOTAL	Total distance (m)
U13	Under 13s
U14	Under 14s
U15	Under 15s
U16	Under 16s
U17	Under 17s
U18	Under 18s
U19	Under 19s

U20	Under 20s
VO_{2max}	Maximal oxygen uptake
WR	Work rate ($m\cdot min^{-1}$)
YoYo IRT1	YoYo intermittent recovery test level 1

CHAPTER 1

Introduction

1.1 Introduction

In England, soccer is the largest sport by participant numbers among females including approximately 900,000 youth female players (The English Football Association, 2017b). Despite the popularity of the sport in a young female population, to date there are only two primary published works of match loads in adolescent female soccer (Ramos et al., 2019; Vescovi, 2014). Match loads are, in part, determined by utilising speed thresholds to sort GPS-derived movement data for analysis. Previous analyses of adolescent female match loads used sprint-speed thresholds that are based on adult female data (Bradley & Vescovi, 2015), potentially underestimating the calculation of high-speed activity for adolescent female players. Quantification of high-speed activity is important in both analysing match performance and in the study of fatigue development in players (Dwyer & Gabbett, 2012; Mohr et al., 2003) meaning accurate quantification of high-speed activity is needed. In evaluating sprint speeds in adolescent female soccer players, maximal sprint speed (MSS) has been observed to plateau around 16 years of age in female soccer players (Vescovi et al., 2011) leading to recommendations of using sprint-speed thresholds for female players 16 years of age or older (Bradley & Vescovi, 2015). However, this leaves a gap in understanding the maximal sprinting abilities of players under 16 years of age and whether previously utilised sprint-speed thresholds appropriately quantify adolescent female soccer match loads in U16 match-play.

Soccer is an intermittent sport with matches consisting of periods of low-intensity work interspersed with high-intensity movements including sprinting. In female soccer, position-specific match loads have been observed, showing that forwards completed a significantly higher number of sprints compared to midfielders, although midfielders ran longer total distances in lower speed zones (Datson et al., 2017; Gabbett & Mulvey, 2008;

Ramos et al., 2019; Vescovi, 2014), suggesting that player position will directly affect the amount of individual high-speed movement a player performs during matches. However, analysing match-play solely using speed thresholds has been shown to underestimate match load, as high-speed thresholds do not account for low-speed, high-intensity movements such as accelerations and decelerations (Dwyer & Gabbett, 2012). High-speed and high-intensity movements have been observed to effect negative neuromuscular responses in players (Nedelec et al., 2014; Thorpe & Sunderland, 2012). This is theorised to occur due to repetitive eccentric actions in the lower limb musculature in running movement and during decelerations (Hewit et al., 2011; Williams, 1985). Such eccentric actions are associated with muscle damage (Proske & Morgan, 2001), which may impact muscle force production (Raastad et al., 2003). Neuromuscular fatigue is a decrease in power generation of a muscle due to exercise (Boyas & Guével, 2011) and is a contributing factor to injuries because of its effects on biomechanical attributes during sporting events, particularly in female athletes (Kernozek et al., 2008). In female soccer players, neuromuscular fatigue has been linked to greater risk of hamstring and anterior cruciate ligament (ACL) injury after simulated match conditions (Delextrat et al., 2013). Understanding sprint-speed abilities specific to adolescent female soccer players and position-specific high-speed and high-intensity movement in match-play could provide insight into the neuromuscular response to match-play and potential increased injury risk in adolescent female soccer players. The relationship between high-intensity movements in match-play and neuromuscular response has not been previously studied in an adolescent female soccer population.

Though neuromuscular fatigue in adolescent female soccer players has been studied, studies have been limited to simulated match conditions in controlled indoor settings (De Ste Croix et al., 2018; De Ste Croix et al., 2015). Findings include increased electromechanical delay and altered neuromuscular control in the lower limb in response to soccer-specific exercise (De Ste Croix et al., 2018; De Ste Croix et al., 2015). However, directly assessing neuromuscular fatigue requires equipment that is often limited to laboratory settings (Carling et al., 2018; Thorpe et al., 2017), limiting the ability to assess fatigue from competitive match-play, especially in adolescent female soccer. Instead, indications of fatigue may be monitored through exercise performance tests that assess neuromuscular responses using techniques that are mobile and can quickly test multiple players, which is important in a team setting (Claudino et al., 2017; Lloyd et al., 2009). Because neuromuscular fatigue is a known contributing factor to lower limb injuries (Kernozek et al., 2008), it is proposed that match loads, including high-intensity movement, be studied during competitive match-play with concurrent neuromuscular response testing to assess indications of fatigue in order to understand potential injury risk due to competitive match-play in a population of female adolescent soccer players.

Importantly, substitute match loads have not been studied in adolescent female football. Youth soccer rules allow for unlimited substitutions in non-cup competition matches (The English Football Association, 2017a). Studies of similar substitution rules in women's NCAA soccer show that match load is affected by substitutions, with many players not completing full matches (Gentles et al., 2018). It could be expected that unlimited substitutions rules would similarly affect adolescent female soccer match loads. One study in women's NCAA soccer observed that substitute work rates were similar upon re-entry into match-play, suggesting that substitutions may also affect neuromuscular response to match-play (Vescovi & Favero, 2014). The effect of substitutions on high-speed activity and high-intensity efforts, positional match loads, and neuromuscular responses to match-play has not been studied in adolescent female soccer. Understanding substitution match load may provide insights useful to training and development in adolescent female soccer as well as assessing the effect of substitution use on neuromuscular responses to match-play in adolescent female soccer.

Therefore, the aim of this research is to explore the neuromuscular response to match load in adolescent female soccer players with consideration to unlimited substitutions. This has implications for (i) assessing neuromuscular response to match-play to provide indications of neuromuscular fatigue due to its contribution to the risk of lower limb injury in soccer; (ii) to inform coaches of position-specific match loads in the context of understanding the neuromuscular response of individual players, including under substitution conditions; and (iii) to provide insight into physical performance during match-play among female adolescent soccer players that might inform training, player development, and injury prevention.

1.2 Research Questions

a) What is an appropriate sprint-speed threshold for classifying maximal efforts during adolescent female soccer match-play?

b) What are overall and position-specific match loads for adolescent female soccer players, including substitute match load?

c) How is neuromuscular response associated with high-speed and high-intensity efforts during adolescent female soccer match-play?

d) How are high-intensity efforts and neuromuscular responses affected by the use of substitutions in adolescent female soccer?

1.3 Research Objectives

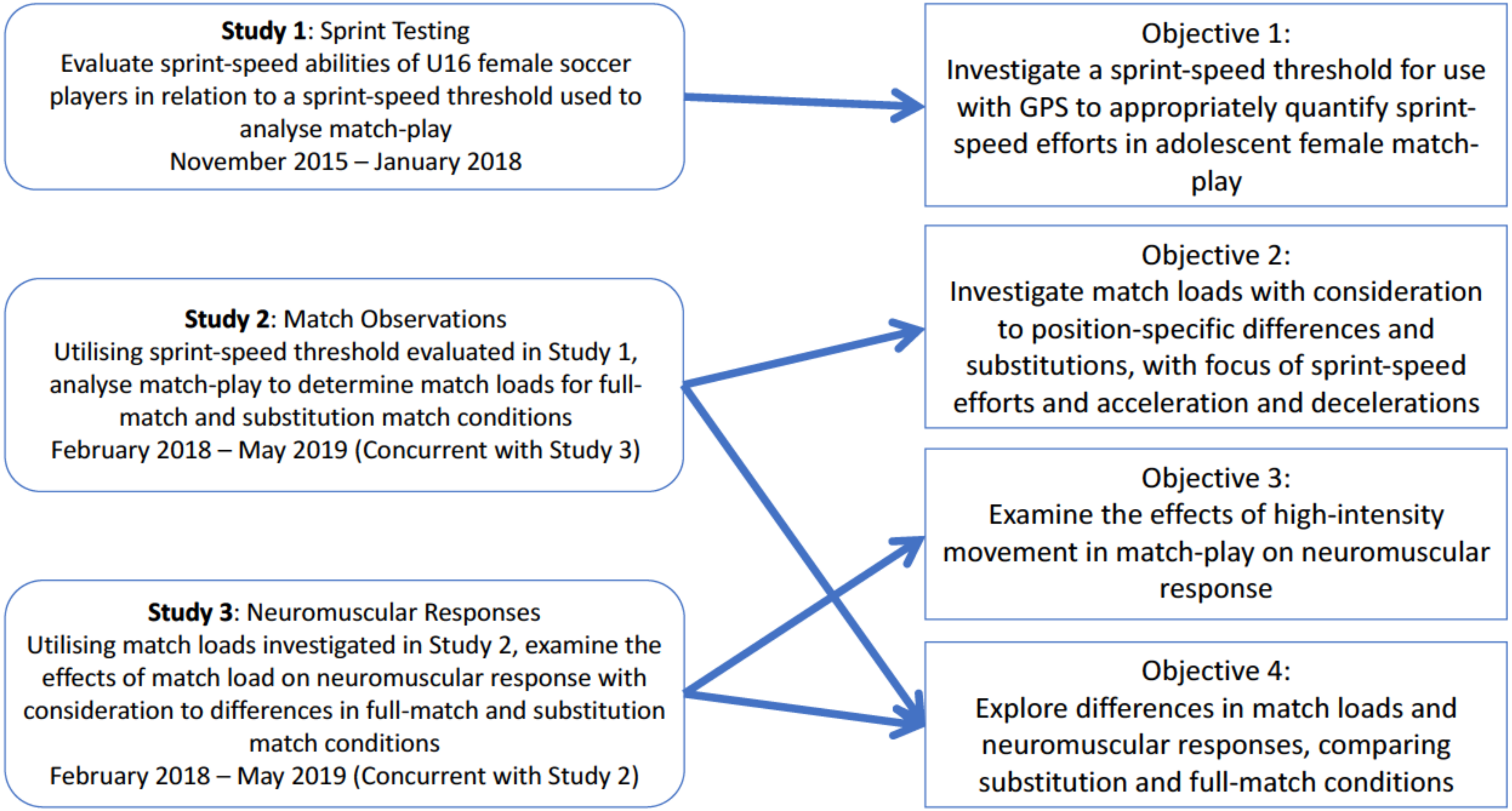
1) Investigate a sprint-speed threshold for use with GPS technology specific to adolescent female soccer players to appropriately quantify sprint-speed efforts in match-play

2) Investigate position-specific and substitute match loads, including maximal sprint efforts and accelerations and decelerations, for adolescent female soccer players during match-play

3) Examine effects of high-intensity movement in match-play on neuromuscular response in adolescent female soccer players

4) Explore differences in match loads and neuromuscular responses, comparing substitutions and full-match conditions in adolescent female soccer players

1.4 Schematic of Research Aims and Timeline



Study 1: Sprint Testing
Evaluate sprint-speed abilities of U16 female soccer players in relation to a sprint-speed threshold used to analyse match-play
November 2015 – January 2018

Study 2: Match Observations
Utilising sprint-speed threshold evaluated in Study 1, analyse match-play to determine match loads for full-match and substitution match conditions
February 2018 – May 2019 (Concurrent with Study 3)

Study 3: Neuromuscular Responses
Utilising match loads investigated in Study 2, examine the effects of match load on neuromuscular response with consideration to differences in full-match and substitution match conditions
February 2018 – May 2019 (Concurrent with Study 2)

Objective 1:
Investigate a sprint-speed threshold for use with GPS to appropriately quantify sprint-speed efforts in adolescent female match-play

Objective 2:
Investigate match loads with consideration to position-specific differences and substitutions, with focus of sprint-speed efforts and acceleration and decelerations

Objective 3:
Examine the effects of high-intensity movement in match-play on neuromuscular response

Objective 4:
Explore differences in match loads and neuromuscular responses, comparing substitution and full-match conditions

CHAPTER 2

Review of Literature

Portions of this Review of Literature are supplemented by a published review included in Appendix 2.1: Hodun, M., Clarke, R., De Ste Croix, M. B. A., Hughes, J. D. (2016). Global Positioning System Analysis of Running Performance in Female Field Sports. *Strength and Conditioning Journal*, 38(2), 49-56. doi: 10.1519/SSC.0000000000000200

2.1 Introduction

In England, soccer is the most widely played team sport among females with large participation among female youth (The English Football Association, 2017b). Despite the popularity of the sport in a young female population, there is limited research available describing the match load of female adolescent soccer players (Ramos et al., 2019; Vescovi, 2014). Research is also limited in describing the neuromuscular response of adolescent female soccer players to match load. Understanding of match load and neuromuscular response is important to developing appropriate training regimes to optimise player performance (Atan et al., 2014), whilst minimising negative outcomes such as injury risk (Whitehead et al., 2018). In order to describe match load and subsequent neuromuscular response to match load, match load must be appropriately quantified for adolescent female soccer players. In this chapter, methods of quantifying match load are reviewed. Current understandings of match load and neuromuscular response in female soccer are also examined.

2.2 Quantifying match load specific to adolescent female soccer

2.2.1 GPS use in soccer

Match load is the total measure of match-play quantified through motion analysis, which is used in soccer to evaluate player movement, develop appropriate training regimes, and monitor fatigue by tracking decreases in player performance (Carling et al., 2008). Motion analysis is possible via video, global positioning system (GPS), and semi-automated camera systems that track player movement. The ability of automated systems such as GPS and semi-automated camera systems to track and quantify movement of multiple players simultaneously has increased their popularity in soccer, compared to time-intensive coding in video analysis (Carling et al., 2008). However, use of semi-automated camera systems is limited due to expense and fixed infrastructure such as stadiums, whereas youth soccer is frequently played in various non-stadium locations (Atan et al., 2014). GPS systems, by comparison, are increasingly used in team sports due to the ease of use and ability to accurately quantify distances covered during sport (Scott et al., 2016).

Using GPS, the displacement of a player is tracked over discrete time periods, enabling the calculation of total distance covered by a player during match-play, as well as velocity and acceleration (Whitehead et al., 2018). Total distance provides an indication of match load, with work rate — distance per time played — providing an indication of match load intensity that allows for comparison between players who differ in time played, such as substitutes (Hodun, Clarke, De Ste Croix, & Hughes, 2016). Quantification of the match load a player performs is further aided by sorting distances covered into speed zones. As highlighted by Dwyer and Gabbett (2012), speed zones have been defined by ranges of velocity, at times with locomotor descriptions assigned (i.e. walking, jogging, running, and sprinting), although there has been a shift away from locomotor descriptors toward using intensity descriptors (i.e. low-, moderate-, and high-intensity motion) instead. Dwyer and Gabbet (2012) questioned this use of intensity descriptors, as some high-intensity movement is performed at low speeds. However, despite increased use of GPS, methods of quantifying motion tracked via GPS are not standardised (Atan et al., 2014). This section of the Review of Literature seeks to inform the reader of the use of GPS to quantify match load, different methods to determine speed thresholds, and to assess speed thresholds in female soccer with special reference to high-speed and high-intensity movement. While the term high-intensity running often refers to a combination of high-speed running and sprint-speed movement in the literature and there is overlap in high-speed and high-intensity movement, this work seeks to differentiate movements by measurement where speed-based measures are referred to by speed descriptors (e.g. using high-speed activity to refer to high-speed running and sprinting (Datson et al., 2019)) and intensity descriptors are used for acceleration-based measures or work rate.

2.2.1.2 A critical appraisal of GPS

GPS was first used to assess athlete distance and speed in research in 1997 (Schutz & Chambaz, 1997) and has since grown in use. Although the term GPS is used colloquially to refer to satellite-based position tracing, the Global Positioning System is a network of satellites run by the US Department of Defence (Townshend et al., 2008). In its early iteration for civilian use, satellite signals were degraded which lowered accuracy of GPS devices but in 2000 this signal degradation was removed (MacLeod et al., 2009; Townshend et al., 2008). After 2000, one early study of raw signal GPS compared speed measurements from the GPS unit to speed measurements taken via timing gates set at 10m intervals; speed and distance of human locomotion measured via GPS were found to be accurate estimations but with decreased accuracy on curvilinear paths (Townshend et al., 2008). Another early study of GPS validity investigated the use of GPS in field sports, including abrupt changes of direction and changes in speed on designated paths of known distance (MacLeod et al., 2009). This study compared GPS-measured speed over short distances in shuttles to speed measured with timing gates, finding speeds measured by GPS and timing gates were highly correlated ($r \geq 0.99$). Distance measurements by GPS for the shuttle runs were found to be significantly different (*p* <0.05); this was due to mean over- or underestimation of ±0.1 m by the GPS compared to distance measured via a calibrated trundle wheel.

A further study by Coutts and Duffield (2010) particularly looked at accuracy and reliability of GPS between three system models, of which one included an accelerometer. This study similarly found distance measures between GPS and measuring tape to be significantly different but reliable, with reasonable distance discrepancies (<5% variation). The researchers noted distance discrepancies may be the result of the actual course taken by the participant wearing the GPS device, which may not exactly follow the course lines set with a trundle wheel or measuring tape (Coutts & Duffield, 2010). These small discrepancies may be the case for any GPS device that is trunk-mounted when compared to ground-measured distances. However, it was noted that the different models demonstrated poor intra-model reliability with a recommendation that data from different GPS models should not be used interchangeably. Interestingly, the reliability of the GPS devices used was good for peak speed measures, but poor for measuring high speed running (>14 $km \cdot hr^{-1}$), especially during non-linear motion. These early studies used 1 Hz GPS systems (Coutts & Duffield, 2010; MacLeod et al., 2009; Townshend et al., 2008). The researchers noted that some movements in intermittent field sports occur in less than 1 second such as short sprint efforts, accelerations, or changes of direction, therefore these movements may not be captured by 1 Hz sampling devices (Coutts & Duffield, 2010).

In intervening years, the technology of GPS systems for sport has advanced with sampling rates now at 10 or 15 Hz. The validity and reliability of these higher sampling devices are further addressed in Chapter 3 (Section 3.1.5 Global Positioning System (GPS) validity and reliability). Increased sampling rates have allowed GPS systems to overcome some of the earlier limitations of accuracy and reliability regarding measures of high speed movements and accurate collection of data during changes of speed and direction noted in earlier studies (Kelly et al., 2014). However, some considerations for researchers using GPS devices remain. One consideration is the manufacturer-specific algorithms used to filter data: while these algorithms are understood to help with data filtering or smoothing, algorithms are also used to interpolate data (Malone et al., 2017). For example, some 15 Hz GPS devices have true sampling rates of 10 Hz with the manufacturer algorithm interpolating the remaining 5 Hz (Aughey, 2011; Johnston et al., 2014). Overall, these algorithms influence the accuracy of GPS devices but are subject to proprietary information protection; without the full disclosure of the algorithms used to filter data, the algorithms can be considered a limitation of such devices (Witte & Wilson, 2004).

Related to algorithm use in GPS data processing is the effect of software updates which provide changes to algorithms used to process data within the manufacturer software. One study compared the same data processed by three software versions of the same GPS manufacturer as the software updates occurred (Buchheit et al., 2014). While distance and peak speed measurements did not significantly change between software updates, acceleration and deceleration counts did significantly change. This consideration of the effects of software updates on GPS data was undertaken using the same device manufacturer as the current study. In light of these findings, GPS software was not updated across the entirety of the current study to allow all data to be processed using the same algorithms and software.

Algorithms also relate to GPS data-derived acceleration and deceleration measures. Because small errors in velocity data are magnified in calculated derivative data like acceleration and deceleration, manufacturer algorithm smooth velocity data to account for these errors (Thornton et al., 2019). Studies of the reliability of GPS-derived acceleration and deceleration are limited. One study assessed the interunit reliability of three 10 Hz GPS systems from different manufacturers including GPS-derived acceleration and deceleration (Thornton et al., 2019). Of the two most common GPS systems used in team sports research (Catapult and GPSports), reported CVs were <7% for low- (<-1 $m \cdot s^{-2}$) and moderate- (<-2 $m \cdot s^{-2}$) intensity decelerations using software-derived data using the manufacturer algorithms. High-intensity decelerations defined as <-3 $m \cdot s^{-2}$ had reported CVs of 10.9% (GPSports) and 12.8% (Catapult) respectively, suggesting caution should be taken in interpreting deceleration data using intensity thresholds. Software-derived accelerations for the two most common GPS systems demonstrated good reliability, with CVs for low-, moderate-, and high-intensity accelerations (>1, 2, and 3 $m \cdot s^{-2}$ respectively) all less than 5% (Thornton et al., 2019). Although limited information is available, GPS systems appear to have good reliability for acceleration and deceleration measures derived from velocity data, although caution should be used in evaluating higher-intensity decelerations.

Finally, a more recent review of validity and reliability studies for GPS devices showed that intraunit reliability is better than interunit reliability (Kelly et al., 2014). For this reason, the researchers recommended that athletes be provided the same GPS device across multiple sessions to mitigate any potential effect. Although GPS interunit reliability is generally lower than intraunit reliability, GPS devices have overall been shown to be valid and reliable especially with more recent technology, including higher sampling rates. There are limitations to GPS as a measurement tool, including the use of non-open source algorithms to process data, software updates, and differences between GPS systems by different manufacturers. But, as the authors of the GPS validity and reliability review argue, while there are data errors of small magnitude (<10%), these errors may be considered acceptable when considering the cost and time benefit that GPS analysis provides in team sports so long as the limitations of the GPS system used are understood (Kelly et al., 2014).

2.2.2 Speed thresholds

In order to analyse match load, speed thresholds are used to categorise movement, though there are no standardised thresholds for female soccer players and high-speed running and sprint thresholds vary across the literature in women's soccer (Hodun et al., 2016). More recently, soccer-specific speed thresholds have been recommended at both international (Datson et al., 2017; Park et al., 2018) and domestic-level, including for professional (Bradley & Vescovi, 2015; Dwyer & Gabbett, 2012) adult female soccer players. Other studies also consider differing methods to define high-speed thresholds and their importance in match performance (Park et al., 2018; Vescovi, 2012a). Quantification of high-speed movement in soccer has been highlighted as an important factor both in match performance analysis and in the study of fatigue development in players (Dwyer & Gabbett, 2012; Mohr et al., 2003). However, there is still a lack of consensus on both thresholds and methodologies for determining speed thresholds in female soccer.

2.2.2.1 Fixed v individualised speed thresholds

Recent studies have examined the use of individualised speed thresholds in soccer, where thresholds are based on various fitness or speed tests for each player (Hunter et al., 2015; Lovell & Abt, 2013). While use of individualised thresholds are beneficial for individual player feedback and exercise prescription (Hunter et al., 2015; Lovell & Abt, 2013), other studies have shown no advantage in using individualised thresholds over fixed thresholds in soccer for assessing repeated sprint sequences in match-play (Nakamura et al.,

2017) or monitoring training dose-response in international players (Scott & Lovell, 2018). In male youth soccer (U11 – U16), use of individualised speed thresholds resulted in fewer detected differences between age groups and between retained and non-retained players for a team (Goto et al., 2015).

By comparison, fixed thresholds are based on the abilities of a population. In match-play, sprint movement analysed using fixed, as opposed to individualised, sprint thresholds could be beneficial for long-term monitoring, as female adolescent players' sprint ability is subject to within-season variations (Emmonds et al., 2020; Taylor et al., 2012). Fixed thresholds could also assist in distinguishing player performance within a team as sprint ability has been shown to differentiate between players that are drafted or not drafted into professional women's soccer teams; players that have higher sprint abilities are more likely to be drafted (Vescovi, 2012b), which aligns with the results from Goto et al (2015) for differentiating between retained or not retained youth players. Comparison of team and individual performances can be undertaken using fixed thresholds (D. Scott & Lovell, 2018). Fixed thresholds additionally allow for understanding of match-to-match variability and between-study comparison (Datson, 2016), as individual thresholds do not allow for comparison between players or teams. Although individualised thresholds can be used for individual player feedback and exercise prescription, this research highlights the ability of fixed thresholds to assess intra-player performance across multiple matches and to compare position-specific and within-team performance (Park et al., 2018), including performance of substitutes with players completing full matches.

2.2.2.2 Determining appropriate speed thresholds in female soccer

A lack of consensus on speed thresholds and methodologies to determine fixed thresholds presents a theoretical problem when choosing how to analyse match-play in female adolescent soccer players, an under-represented population in the literature. Previously in some studies, thresholds have been arbitrarily chosen (Dwyer & Gabbett, 2012). For example, one such method has been to use percentages of player maximal sprint speed (MSS) to set fixed speed thresholds. However, this method has been shown to lack robust reasoning for use other than quantifying sprint-speed motion and resulted in large misinterpretations of high-speed activity and comparison between players (Hunter et al., 2015).

Other systematic approaches to determining thresholds have also been undertaken, including retroactively determining speed thresholds based on observed match loads. One set of recommended thresholds was established from 1 Hz GPS match-play data of a small sample ($n = 5$) of domestic-level (Australian state league) female adult soccer players (Dwyer & Gabbett, 2012). Average distribution of the frequencies of velocities throughout a match were fitted to 4 Gaussian curves and intersecting points of the curves were used to determine thresholds as demonstrated in Figure 2.1 (Dwyer & Gabbett, 2012). This resulted in thresholds of ≥ 0.2 (walk), ≥ 1.7 (jog), ≥ 3.4 (run), and ≥ 5.4 (sprint) $m \cdot s^{-1}$ that have been used to some extent in female soccer (Hewitt et al., 2014; Mara et al., 2015; Vescovi, 2014; Vescovi & Favero, 2014). Although statistical modelling for speed thresholds can provide useful understanding of match data, the small sample size and lack of reasoning for the speed transitions based on the intersections of Gaussian curves suggest that the low-speed thresholds have limited justification (Park et al., 2018).

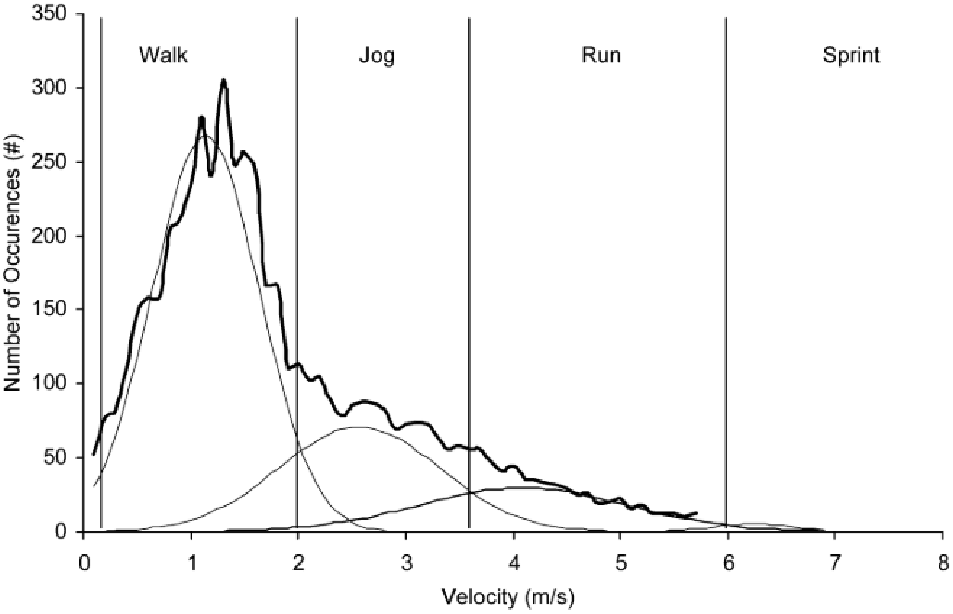


Figure 2.1 A graph demonstrating the methodology of determining speed thresholds from men’s soccer match-play, with four Gaussian curves showing best fit for speed distribution. Points where the curves intersect are the determined thresholds. Adapted from “Global Positioning System Data Analysis: Velocity Ranges and a New Definition of Sprinting for Field Sport Athletes,” by D. Dwyer and T. Gabbett, 2012, *Journal of Strength and Conditioning Research*, 26(3), p. 819.

A recent study analysed different methods of retroactively determining speed thresholds using statistical modelling of match data from international adult female players from three seasons of match data (Park et al., 2018). Park et al (2018) used a Spectral Clustering algorithm to examine match-play velocity data from 227 match observations. Compared to the statistical method of using the intersections of Gaussian curves, Spectral Clustering accounts for players transitioning through speed zones (i.e. a player accelerating covers distance in different speed zones), calculating four partitions in smoothed speed transition data. This technique results in recommended wider-ranging low-speed band (0-3.46 $m \cdot s^{-1}$, or 12.5 $km \cdot h^{-1}$), alongside three higher thresholds of high-speed running (≥ 3.46 $m \cdot s^{-1}$) —which is similar to the jog threshold (3.4 $m \cdot s^{-1}$) calculated by Dwyer and Gabbett (2012)

—very-high speed running (≥ 5.29 m·s^{-1}), and sprinting (≥ 6.26 m·s^{-1}) (Park et al., 2018). However, the thresholds are derived from international players from one of the top teams in the world. Another study evaluating match loads in international players suggests the use of speed thresholds utilised in male match-play, as these may be more appropriate for international-level female players compared to thresholds derived from a small, domestic sample of female players (Datson et al., 2017). However, the application of these thresholds as recommended for elite international players, in particular the high-speed and sprinting thresholds, might result in the underestimation of high-speed movement in non-international and adolescent players. Further, in the absence of large data sets to retroactively determine speed thresholds in adolescent female soccer, other methods of determining speed thresholds may be considered.

In contrast to statistical modelling methods, thresholds for high-speed and sprint-speed running based on sport-specific performance parameters, specifically maximal aerobic speed and maximal sprint speed have been proposed (Bradley & Vescovi, 2015). Bradley and Vescovi (2015) recommended a high-speed running threshold of 15.5 km·h^{-1} as this is approximately the value of maximal aerobic speed for adult female soccer players. In one study comparing professional men's and women's match movement, total distances in lower-speed zones <15 km·h^{-1} (4.17 m·s^{-1}) were not different between genders (ES: 0.1-0.3) and the greatest differences in distance ($p > 0.01$) were in high-speed zones >4.17 m·s^{-1} (Bradley et al., 2014). Differences in gender for movement at speeds >4.17 m·s^{-1} coincide with the recommended generic high-speed threshold based on maximal aerobic speed and may merit use in female soccer because the threshold is based on both a physiological performance measure and allows for potential comparison to male match-play. The authors report unpublished data of YoYo IRT1 scores in 26 U17 female soccer players corresponds to a

MAS of 15 km·h^{-1} (4.17 m·s^{-1}), further justifying the use of 15 km·h^{-1} (4.17 m·s^{-1}) in adolescent cohorts. Similarly, Bradley and Vescovi (2015) used assessments of maximal sprint speed to determine sprint-speed thresholds, suggesting 20 km·h^{-1} (5.56 m·s^{-1}). This threshold was derived from MSS testing of adult female soccer players (Vescovi, 2012b), aligning to 80-85% of reported MSS as players in the study were found to reach 80-85% of MSS within 10 m of a standing start. Bradley and Vescovi (2015) acknowledged that differences in maximal sprint speed are seen up to 16 years of age in youth female soccer players (Vescovi et al., 2011) and suggest the use of the sprint speed threshold for players over 16 years of age. This leaves a gap in the literature as to whether players in U16 age brackets who are by definition younger than 16 years of age can achieve similar sprint speeds. Further, the findings of both Park et al (2018) and Bradley et al (2014) suggest the use of wide low-speed zones and smaller high-speed zones provides appropriate comparisons of performance, with emphasis on differentiating important soccer performance variables between players, teams, or populations using high-speed and sprint-speed thresholds. As current recommendations for sprint-speed thresholds are based on adult female data, determining appropriate sprint-speed thresholds is still of concern in adolescent female soccer who are younger than 16 years of age.

2.2.3 Sprint-speed thresholds for adolescent female soccer match-play

2.2.3.1 Sprint-speed thresholds used to assess female adolescent match-play

To date, only two studies have reported on female adolescent match-play (Ramos et al., 2019; Vescovi, 2014). Both studies utilised thresholds established for adult female soccer players as shown in Table 2.1 (Dwyer & Gabbett, 2012; Vescovi, 2012b). High-speed thresholds used in the studies of adolescent female match-play were derived from MSS testing (Vescovi, 2012b) and the analysis of high-speed movement in match-play (Vescovi, 2012a). In Vescovi (2012b), a cohort of female soccer players ($n = 140$) trialling for professional teams were tested for MSS over 35 m with intermediate splits using timing gates. From a standing start, players had recorded speeds of 18 km·h^{-1} (5.0 m·s^{-1}) over the first 10 m and 21.2 km·h^{-1} (5.89 m·s^{-1}) over 0-20 m. Mean speed from the 10-20 m split was 25.9 km·h^{-1} (7.19 m·s^{-1}) and mean speed from the final 15 m of the 35 m sprint test was 27.3 km·h^{-1} (7.58 m·s^{-1}), the fastest split reported (Vescovi, 2012b). In analysing high-speed movement in competitive match-play for 139 full match observations from 71 professional female players, Vescovi (2012a) subcategorised high-speed movement ≥18 km·h^{-1} (5.0 m·s^{-1}) into four discrete zones into which each sprint was sorted. The increase of sprint duration and sprint distance resulted in a sprint placing into a higher speed band. Of 5,019 recorded high-speed events ≥18 km·h^{-1} (5.0 m·s^{-1}), a total of 548 sprints or 11% of recorded events were above 25.0 km·h^{-1} (6.94 m·s^{-1}). The average distance of all high-speed events ≥18 km·h^{-1} (5.0 m·s^{-1}) was 15.1 (±9.4) m, compared to the average distance of 29.0 (±9.8) m for events recorded above 25.0 km·h^{-1} (6.94 m·s^{-1}) (Vescovi, 2012a). This shows that although professional-level female players are capable of reaching speeds in excess of 25 km·h^{-1}, a high-speed threshold of >25 km·h^{-1} would not capture all sprint efforts that occur as longer distances are required to reach these maximal speeds, so use of a lower threshold to quantify sprinting in match-play would be appropriate.

Table 2.1 Speed thresholds used in Vescovi (2014) and Ramos et al (2019)

Speed threshold descriptors	$km \cdot h^{-1}$	$m \cdot s^{-1}$	Speed zones
Standing & walking	0-6.0	0-1.67	Low-speed thresholds based on Dwyer and Gabbett (2012)
Jogging	>6.0	>1.67	
Low-speed running	>8.0	>2.22	
Moderate-speed running	>12.0	>3.33	
High-speed running	>15.5	>4.31	High-speed thresholds based on Vescovi (2012a) and (2012b)
Sprinting	>20.0	>5.56	

2.2.3.2 Sprinting in adolescent female soccer match-play

Two studies have reported on female adolescent match-play performance: the first for U15, U16, and U17 high-level players in the United States (Vescovi, 2014), and the second for U17 players for the Brazilian national team (Ramos et al., 2019), both using the high-speed and sprinting thresholds described in Table 2.1. In match-play across three age groups studied by Vescovi (2014), the U15 age group had significantly less total sprint distance in a match, lower number of sprints, and lower work rate compared to both U16 and U17 groups, in addition to significantly less total high-speed running distance compared to the U17 group (Vescovi, 2014), suggesting the sprint-speed threshold may be too high for younger players. However, the study found no significant difference in maximal speed and average sprint distance during match-play between the U15, U16, and U17 age groups. Ramos et al (2019) compared high-intensity movement between U17, U20, and senior Brazilian national teams. Senior players demonstrated higher total high-speed and total sprint distance than U17 players; U20 players also demonstrated higher total high-speed distance than U17 (Ramos et al., 2019), showing the adolescent age group had decreased use of sprint ability within match-play compared to adult players. While differences observed in both studies, in both number of sprints and total sprint distance increasing with chronological age suggest differences in movement analysis parameters may be due more to factors other than sprint speed, sprint ability differences between adolescents and adults have been shown within match-play. However, further testing beyond the limited available data is necessary to determine if age-matched cohorts have similar sprint ability and use of sprinting in match-play.

2.2.3.3 Maximal sprint speed in adolescent female soccer

Player sprint ability is normally assessed with a linear sprint test, a readily available physical fitness test that does not require a laboratory and which results are easily determined. Although the use of player MSS to set fixed-speed thresholds as percentages of MSS has been shown to lack robust reasoning (Hunter et al., 2015), using MSS specifically to determine a sprinting threshold, as opposed to all thresholds as a percentage of MSS, is both logical and ecologically valid (Datson, 2016; Mendez-Villanueva et al., 2011). A study of the impact of MSS on maximal sprint speed in matches in male adolescent players demonstrated that players with higher MSS corresponded to higher maximal sprint speed in matches (Mendez-Villanueva et al., 2011). Additionally, regardless of sprint ability, players utilised a high percentage of their individual MSS (84-91%) during matches. This demonstrates the importance of understanding how fast players are able to run in order to correctly evaluate match-play, even if players do not use their full sprint ability during match-play. The use of 84-91% of MSS per player within a match (Mendez-Villanueva et al., 2011) also aligns with the higher end of the recommendation to use 80-85% of MSS as a sprint-speed threshold in female soccer (Bradley & Vescovi, 2015). Use of a player’s or cohort’s tested maximal sprint speed as a sprint threshold may underestimate sprinting in match settings, therefore using a percentage of tested MSS has reason in match-play analysis.

Previous research on the sprint abilities of trained female adolescent soccer players from 14-19 years of age provide varied data (Datson, 2016; Emmonds, Sawczuk, et al., 2018; Hoare & Warr, 2000; Vescovi et al., 2011). Methods and results where available from each study are collated in Table 2.2. A recent study in high-level adolescent female soccer in RTCs in England (U16, n = 32) used timing gates to monitor performance of a 30 m linear sprint including a 0-10 m split throughout a single soccer season, observing 1.90 s for the 0-10 m split and 4.70 s for the 30 m linear sprint (Emmonds et al., 2018). Similar testing with U15 and U17 national team players in England (n = 382) recorded mean 30 m sprint times using timing gates; though moderate differences were observed between U15 and U17 players for 30 m linear sprint times (ES = 0.64), recorded times were similar between age groups (4.78 and 4.65 seconds, respectively) (Datson, 2016). An Australian study using timing gates to assess 10 and 20 m linear sprint speed for 15-19 year olds as part of an soccer talent identification (ID) trial, compared sprint results for all trialists and for selected players (Hoare & Warr, 2000). Selected players (n = 17) were 3% faster over 10 m and 4% faster over 20 m compared to the mean of all trialists. Results show some variation in adolescent sprint speeds. This underscores the need to test the sprint ability of the cohort observed in the current study for match load, as different cohorts may have different sprint abilities requiring different sprint-speed thresholds for match load analysis.

Table 2.2 Results from linear sprint speed tests of female soccer players as measured via timing gates

	Age group	n	Test length (m)	TG placement (m)	Split distance (m)	Time (s)	Speed (m/s)
Hoare & Warr, 2000	Trialists; 15-19y	59	20	0, 5, 10, 20	0-10	2.08 ± 0.18	4.81
					0-20	3.63 ± 0.23	5.51
	Selected; 14.5-18y	17	20	0, 5, 10, 20	0-10	2.01 ± 0.08	4.98
					0-20	3.47 ± 0.14	5.76
Vescovi et al, 2011	14-17y	223	36.6	0, 9.1, 18.3, 27.4, 36.6	0-9.1	n/a	4.69 ± 0.26
					0-18.3	n/a	5.48 ± 0.27
					0-27.4	n/a	5.90 ± 0.31
					9.1-18.3	n/a	6.59 ± 0.37
					18.3-27.4	n/a	7.00 ± 0.39
Datson, 2016 (unpublished thesis)	U17	20	30	0, 5, 10, 20, 30	0-10	1.870 ± 0.053**	5.35
					0-20	3.31 ± 0.09**	6.04
					0-30	4.68 ± 0.12**	6.41
	U15	60	30	0, 5, 10, 20, 30	0-10	1.909 ± 0.098**	5.24
					0-20	3.24 ± 0.14**	6.17
					0-30	4.79 ± 0.24**	6.26
Emmonds et al, 2018	U16	32	30	0, 10, 30	0-10	1.90 ± 0.16*	5.26
					0-30	4.70 ± 0.31*	6.38

Data presented as mean ± SD where available; n = number of participants; TG = timing gate; y = years of age; n/a = not available; *Data from mid-season testing; **Data from Trial 1

2.2.4 Effect of maturation on sprint speed ability

A cross-sectional study in female soccer players from 12-21 years of age (n = 414) evaluated linear sprint speed over 36.6 m using timing gates at 9.1, 18.3, 27.4, and 36.6 m, the results of which are shown in Figure 2.2 (Vescovi et al., 2011). A plateau in sprint speed is noted where significant differences in speed between subsequent age groups were no longer observed from 15 years in the 2nd 9.1 m split, from 14 years in the 3rd 9.1 m split, and for the 4th 9.1 m split at 17 years, though small increases are noted beyond these ages such as a 2.4% difference between the 14-17 age group compared with the older 18-21 age group. A similar small but non-significant difference (2.0%) in sprint speed between junior (U18) and senior (>18 years) players was also noted in another study, with senior players observed to be faster over 15 m (Mujika et al., 2009), suggesting increases in sprint speed may continue beyond later adolescence. Linear sprint speed begins to plateau at 13-14 years for the 2nd and 3rd splits (Vescovi et al., 2011). The observed plateaus correspond closely with estimated age of post-peak height velocity (PHV) in girls, where development of physical qualities and performance measures begin to plateau from the age of 13 (Catley & Tomkinson, 2013; Malina et al., 2004; Malina et al., 2010).

Though the plateau in sprint speed corresponds with a plateau in maturation, differences in sprint speed are still noted between age groups of similar levels (international) (Datson, 2016) and between players of differing performance (Hoare & Warr, 2000), suggesting there may be a training element involved in increasing sprint speed. The current body of knowledge suggests adolescent female soccer players could be capable of reaching speeds considered to be sprints using thresholds determined from female adult soccer players. However, with the presented range of sprint speeds and varying sprint test distances for similar adolescent age groups, further research of sprint speed in adolescent female soccer players is warranted.

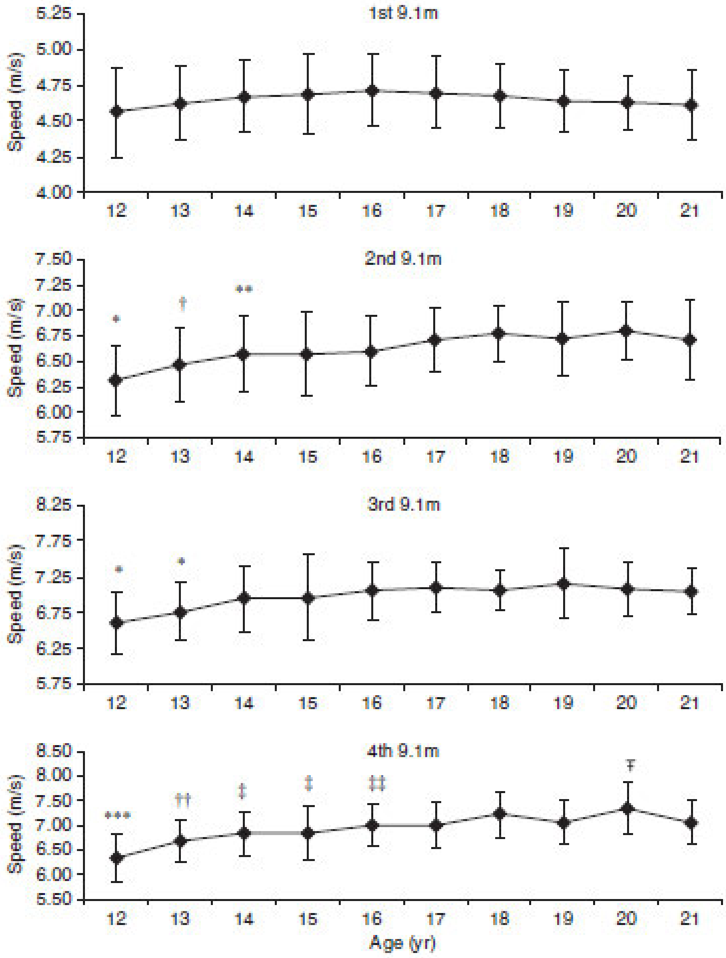


Fig. 3. Linear sprint speed for individual splits for each age. Sample size for each year of chronological age were: 12 (*n* = 33), 13 (*n* = 45), 14 (*n* = 59), 15 (*n* = 72), 16 (*n* = 64), 17 (*n* = 28), 18 (*n* = 34), 19 (*n* = 27), 20 (*n* = 27), and 21 (*n* = 25)-year-olds. *Different compared with 14–21 years. **Different compared with 18 and 20 years. ***Different compared with all ages. †Different compared with 17–21 years. ††Different compared with 16–21 years. ‡Different compared with 16, 18–20 years. ‡‡Different compared with 18–20 years. †Different compared with 17, 19, and 20 years.

Figure 2.2 Results of a cross-sectional study of linear sprint speed in female soccer players, 12 – 21 years of age. Adapted from “Physical performance characteristics of high-level female soccer players 12-21 years of age,” by J. Vescovi et al, 2011, Scandinavian Journal of Medicine & Science in Sports, 21(5), p. 673.

2.3 Match load in female soccer

With speed thresholds applied to GPS data collected from match-play, analysis of match load can be conducted. GPS software is programmed to calculate measures of distance covered by a player during match-play from GPS displacement data based on provided speed thresholds (Whitehead et al., 2018), sorting completed distances into speed zones. Acceleration and deceleration can also be derived from calculations of speed based on displacement. With recent advances in technology, it is possible to simultaneously quantify player movement across a pitch and physiological responses to match-play with the development of GPS and heart rate (HR) monitoring that is synced to GPS. This allows for simultaneous monitoring of external measures of match load and HR as an indication of internal responses to match load (Carling, 2013). Understanding of match load is important to inform training and to assess player and team performance (Datson et al., 2017; Reilly, 2005), however, there is limited data available on adolescent female soccer to inform training. This section of the Review of Literature seeks to inform the reader of match load measures assessed via GPS in female soccer and particularly in adolescent female match-play.

2.3.1 Total distance and work rate

Total distance covered in match-play is the total displacement measured by GPS, and is an indicator of cumulative physical load in motion analysis (Hodun et al., 2016). However, an inherent problem in use of total distance in motion analysis is evident when matches are of differing durations, as is the case in female adolescent soccer, where U16 players have 80-minute matches compared to 90-minute matches in adult soccer, or in the event of substitution where players do not complete an entire match. To remedy this, measures of work rate (total distance/time played) are used to compare player performance (Hodun et al., 2016) and to assess intensity of physical load performed by players. A recent review (Hodun et al., 2016) of running performance in female field sports highlighted total distances in adult female soccer during match-play, observing ranges of 8533 – 9997 m per 90 minute matches.

In one study of adolescent female soccer players, U16 total distance was observed to be 8024 m per match and 8558 m for U17 players; however, due to differences in match time played (U16: 80 min; U17: 90 min) the work rates of both age groups were identical at 100 $m \cdot min^{-1}$ (Vescovi, 2014), suggesting players in both age groups work at the same intensity during match-play but the older age group maintained the intensity for a longer duration. This finding may inform training in that U16 and U17 players would include training exercises with similar intensities to replicate match loads. This underscores the importance of using work rate in assessing match load.

2.3.2 High-speed running during match-play

The quantification of high-speed activity (HSA) in match-play has received focus in the literature for evaluating both player performance (Krustrup et al., 2005; Ramos et al., 2019) and to monitor markers of fatigue (Andersson et al., 2010; Mohr et al., 2003, 2008). HSA refers to high-speed and sprint-speed movement. In match-play, HSA differentiates between competition levels and age groups in female soccer, with more HSA occurring in higher competition levels (Andersson et al., 2010; Mohr et al., 2008) and older players covering more HSA distances compared to younger players (Ramos et al., 2019). High-speed activity also differentiates between male and female professional players where female players cover similar distances to male players below the HSA threshold but significantly lower distances than males above HSA thresholds (Bradley et al., 2014).

In high-level adult female soccer, VO_{2max} and YoYo IR test performance were highly correlated ($r = 0.81$ and 0.82, respectively) to HSA in match-play (Krustrup et al., 2005) showing that HSA is closely related to players' tested aerobic capacity. It has been suggested that comparatively lower HSA in female players is due to pronounced muscle glycogen depletion in females in later match stages (Krustrup et al., 2010) as female soccer players have lower aerobic capacities than male players of similar competition level (Mujika et al., 2009). Mujika et al (2009) also found significant differences ($p < 0.001$) in aerobic capacity between senior female players and junior (U18) players, with U18 players completing 48.2% less distance compared to senior players in the YoYo IRT1. Players with higher aerobic capacity appear to be able to complete more HSA which may reflect selection to higher competition levels and training status (Krustrup et al., 2005).Together, these studies highlight the importance of HSA in differentiating player performance and physical ability in crucial match movements. Quantifying HSA in match-play and understanding high-speed match load can inform adolescent-specific training development and allows for evaluation and tracking of adolescent player performance.

2.3.2.1 Decreases in HSA during match-play – indication of fatigue onset

Quantified match load in match-play also provides an indication of fatigue onset within a match, with decreases observed in HSA distance in later match stages, a phenomenon commonly reported in women's soccer literature (Andersson et al., 2010; Datson et al., 2017; Hewitt et al., 2014; Mara et al., 2017a; Mohr et al., 2008; Ramos et al., 2017; Strauss et al., 2019; Vescovi, 2014). In one set of international women's soccer players, reductions in HSA (24 – 27%) were observed during the last 15 minutes of matches when the same players were observed both in international matches and in domestic matches (Andersson et al., 2010). Andersson et al (2010) also noted larger reductions in HSA during the final 30 minutes of international compared to domestic matches, indicating a higher degree of fatiguing effect during match-play for higher competition levels. This may be linked to the observation that more HSA occurs in higher competition levels (Andersson et al., 2010; Mohr et al., 2008), where higher match loads elicit a higher fatigue response. Decreases in HSA during the final periods of a match were also observed in female players of differing playing standards (international and domestic players) (Mohr et al., 2008). Generally, declines in player performance during a match occur regardless of playing standards (international players in international or domestic matches) or player performance level (international players v domestic players) (Andersson et al., 2010; Mohr et al., 2008).

2.3.2.2 HSA in adolescent female match-play

In one study on adolescent female match loads (Vescovi, 2014), match observations showed reductions in HSA for U16 and U17 players in conjunction with increased low-speed movement between 1st and 2nd half, however reductions were not clear in U15. This may reflect a positive maturation-related neuromuscular response to exercise and that reductions in observed match load arise as a protective mechanism to limit peripheral fatigue development (Amann, 2011; Marshall et al., 2014; Sidhu et al., 2013) although more research is warranted within this population. However, statistical significance was not reported for 1st and 2nd half differences, as this was not the focus of the study (Vescovi, 2014), limiting the strength of this inference. Significant decreases in total distance between 1st and 2nd half were observed for youth female players (U13) in 7-a-side 50-minute matches, along with nonsignificant decreases in running at speeds >13 $km \cdot hr^{-1}$ (3.6 $m \cdot s^{-1}$) (Barbero-Álvarez et al., 2008). The reduction in distances performed in different speed zones has also been reported in male professional soccer (Bradley & Noakes, 2013; Mohr et al., 2003). Observed declines in quantified movement in later stages of matches occurred regardless of the score differential (Mohr et al., 2003) and match performance was not affected by match importance (Bradley &

Noakes, 2013). This suggests that fatigue is a factor in the observed reduction of movement from 1st to 2nd half as opposed to a controlled reduction in match load by players due to determined match outcomes. In addition to the potential neuromuscular response mechanism, these match load decrements may also reflect depletion of glycogen stores in later match stages (Krustrup et al., 2010). Together, these studies highlight a reduction in match load, particularly with regards to high-speed activity, in the later stages of match-play, indicative of the effects of fatigue during match-play.

2.3.3 Measures of maximal running efforts

2.3.3.1 Repeated sprints in match-play

Repeated sprint ability (RSA), or a player’s ability to perform a successive speed-defined sprint closely following a preceding sprint with little recovery time between sprints, is related to HSA and has been cited as a similarly important aspect of player performance in soccer (Jones et al., 2013). In domestic and international women’s soccer, increasing recovery times were observed between subsequent bouts of repeated sprints (RS) during each half and longer recovery times between RS bouts in the 2nd half compared to the 1st (Gabbett et al., 2013); players were observed to increase the amount of low-speed movement between RS bouts. The occurrence of increased recovery times in both competition levels suggest the increases are due to fatigue. However, the study used subjective video analysis to determine sprinting efforts as opposed to defining movement using speed, leading to concerns about the accuracy of the observed number of sprints; sprinting distances were not reported.

Further, the utilisation of RS as defined by varying speeds and between-sprint recovery times in match-play has been questioned, as few RS bouts occur in match-play, including in international men’s soccer (Schimpchen et al., 2016), and in male adolescent soccer where some players (30% of an U17 team) did not perform any RS bouts across several matches (Buchheit et al., 2010). In a recent study of RS and repeated high-speed running in adult female international matches, 37% of all players (of 107 players across 13 teams) did not complete any RS bouts, with approximately one RS bout occurring per match (Datson et al., 2019). A similar lack of RS was observed in adult female soccer across 10 matches, averaging only 3.3 RS bouts in a match per player with some players having no observed RS bouts, even when using individualised speed thresholds (Nakamura et al., 2017). In the same study, reductions from the 1st to 2nd half and differences between playing positions were noted for RSA. These reductions in RS from 1st to 2nd half align with decreases in HSA within match-play in other studies, highlighting the relationship between these variables. However, there is clear potential to underestimate match load performed by players if few RS bouts occur and if some players do not perform any RS bouts at all during matches. A lack of RS in match-play is likely due to technical and tactical restrictions (Nakamura et al., 2017). This limits the use of RS in match-play to indicate performance decrements and possible onset of fatigue.

2.3.3.2 Acceleration and deceleration in match-play

This questioning of the validity of RS for use in soccer match-play and lack of observed RS in match-play has led to a shift towards the use of acceleration as an analysis tool for high-intensity match load (J. C. Barbero-Álvarez et al., 2014). The ability to accelerate in soccer is key to both defensive and offensive actions (Faude et al., 2012; Stølen et al., 2005). Accelerations and decelerations have high metabolic costs (di Prampero, 2005; Osgnach et al., 2010) and the frequency of acceleration and deceleration efforts in match-play has been linked to decrements in neuromuscular performance (Nedelec et al., 2014), which underscore the need to quantify such efforts. However, exclusive use of speed zones to categorise movement in match-play underestimates short-duration maximal efforts because they do not reach high-speed thresholds (Varley & Aughey, 2013). Similar to speed thresholds, there is a lack of consensus on acceleration and deceleration thresholds in the literature. However, thresholds of acceleration and deceleration focus on two categorical measures — high-intensity and low-intensity accelerations and decelerations — with 2.0 m·s^{-2} (Mara et al., 2017b; Ramos et al., 2017) or 2.26 m·s^{-2} (Meylan et al., 2017; Trewin et al., 2018b) used for high-intensity efforts in female soccer analysis. Further, these studies simply use these thresholds to count accelerations and deceleration in match-play. The additional analysis of maximal efforts defined using acceleration could provide further insight into match load and fatigue onset in match-play compared to solely counting the number of sprints above a sprint speed threshold (Dwyer & Gabbett, 2012).

A recent study of accelerations and decelerations in domestic female adult soccer reported decreases in accelerations (>2.0 m·s^{-2}) and decelerations (<-2.0 m·s^{-2}) from 1st to 2nd half ($p < 0.001$; $d = 0.468 – 0.471$) (Mara et al., 2017b). The study found these decreases between halves occurred across all accelerations and decelerations as categorised by starting and final speed (i.e. decelerating from a sprint speed >5.4 m·s^{-1} or accelerating within a low speed zone <3.4 m·s^{-1}), similar to decreases in HSA in other studies. In international U20 players, high-intensity accelerations >2.26 m·s^{-2} corresponding to 80% of maximal acceleration in sprint testing were counted during match-play; mean high-intensity accelerations per minute across all matches was 1.78 ± 0.67 compared to 0.73 ± 0.25 high-speed efforts per minute (>16.5 km·hr^{-1}, 4.6 m·s^{-1}) (Meylan et al., 2017). A study by the same research group using the same acceleration and speed thresholds observed a mean of 1.79 ± 0.37 high-intensity accelerations per minute in international female players (ages 15 – 34) (Trewin et al., 2018b), similar to that observed in international U20 players. Trewin et al (2018b) also reported 0.62 ± 0.19 high-speed efforts per minute and 0.21 ± 0.09 sprint-speed efforts per minute (>5.55 $m \cdot s^{-1}$) however, the impact of the large age range from adolescent to adult in the study is not examined nor is it clear how many adolescent players were included compared to adult players. While the speed threshold for HSA efforts is slightly higher than the threshold for HSA used in other adolescent female match-play analyses (>4.3 $m \cdot s^{-1}$), the large differences between the number of HSA efforts defined by speed (59%) or sprint-speed efforts per minute (88%) and the number of high-intensity accelerations further points to the use of both speed and acceleration to fully describe a player's match load.

2.3.3.3 Acceleration and deceleration in adolescent female match-play

One study has reported acceleration and deceleration efforts in adolescent female match-play for U17 international players (n = 14) using 1.0 and -1.0 $m \cdot s^{-2}$ for acceleration and deceleration thresholds, respectively (Table 2.3) (Ramos et al., 2019). Between-position differences were not analysed, though it is noted that Fullbacks were observed to complete a higher amount of accelerations and decelerations compared to other positions; Midfield completed the lowest amount of accelerations, and Midfield and Central Defenders completed similar lower amounts of decelerations compared to the other positions. In comparing accelerations of U17 to U20 and senior international players, Ramos et al (2019) found U17 Forward and Midfield acceleration counts were significantly fewer than U20 and senior players, U17 Central Defender counts were significantly less than senior but similar to U20, and Fullback acceleration counts were the same across the three age groups. For decelerations, U17 results were significantly lower than both U20 and senior for all positions.

Though small sample sizes per position are a potential confounding factor, this is the first description of adolescent acceleration and deceleration in match-play. It is also indicative of the need to improve player acceleration and deceleration ability in order to compete at higher playing levels (Ramos et al., 2019). Further understanding of acceleration and deceleration in adolescent female match-play is warranted and would assist in developing appropriate training specific to adolescent female soccer players and provide further indications of performance decrements during match-play.

2.3.4 Match load in adolescent female soccer

To date, assessment of match loads in adolescent match-play has only been undertaken in two previous studies (Ramos et al., 2019; Vescovi, 2014). A summary of match loads for both studies is shown in Table 2.3. In Ramos (2019), U17 players had lower match loads over the same match duration compared to U20 and senior players for all variables with the exception of sprinting distance, where U17 players completed less sprint distance than senior players, but differences were unclear between U17 and U20 players. Differences in playing positions within the U17 age group are noted based on the means in Table 2.3: similar total match distances were completed by Midfield and Fullback players, and those distances were higher compared to Central Defender and Forward, along with subsequent higher work rates (total distance per minute played). Midfield sprinting distance was substantially lower compared to Forward and Fullback; Fullback high-speed running was higher than other positions, as was the number of accelerations; Central Defender decelerations were substantially lower compared to Forward and Fullback. Statistical significance of the differences in means between positions within the age group was not reported in the study.

In Vescovi (2014), similar positional differences were reported using general playing position classifications: Midfield total distance and work rate was significantly higher compared to Defender; Midfield sprinting distance and number of sprints were significantly lower than Forward; similar positional differences were observed in both the 1st and 2nd halves of match-play. In comparing adolescent age groups (U15, U16, and U17), U15 players had significantly lower total distance and lower work rates compared to U16 and U17 players, respectively. Players in the U15 age group also performed significantly lower sprinting compared to U16 and U17, respectively and significantly lower high-speed running compared to U17. Time played was used as a covariate in the analysis to account for difference in the length of match half.

Comparison of match-play variables between the studies cautiously suggests similar match loads but higher match intensity in high-level domestic players competing in national championships (Vescovi, 2014) compared to international adolescent players (Ramos et al., 2019), though it is difficult to account for varied match length in Vescovi (2014) compared to 90-minute matches in Ramos et al (2019). Importantly, differences in match load between playing positions in adolescent match-play reflect similar differences between playing positions in domestic and international women's soccer: other studies (Andersson et al., 2010; Datson et al., 2017; Gabbett & Mulvey, 2008; Hewitt et al., 2014; Vescovi, 2014) have observed that Midfield players cover higher total distances compared to Defenders. Forward players have been observed to sprint more during matches compared to Midfield and Defenders (Gabbett & Mulvey, 2008; Mohr et al., 2008; Vescovi & Favero, 2014). Although playing position classifications are not uniform across studies, it is also noted that further differences have been observed between positions using wide and central position classifications, with attacking players completing more sprint-type running and central players completing lower total distances (Datson et al., 2017; Ramos et al., 2017). Both adult and adolescent match-play analyses confirm that match load is specific to player position, and examination and monitoring of match loads and subsequent training to enhance match-play performance should account for these between-position differences.

Table 2.3 Summary of match loads observed (mean ± SD) in studies of adolescent female soccer players (Ramos et al., 2019; Vescovi, 2014)

Study	Vescovi (2014)			Ramos et al (2019)			
Player age group(s)	U15, U16, and U17 players (n = 89)			U17 players (n = 14)			
Position classification	Forward	Midfield	Defender	Forward	Midfield	Fullback	Central Defender
Number of participants	n = 8	n = 25	n = 56	n = 9	n = 17	n = 10	n = 7
TOTAL (m)	7952 ± 299	8449 ± 170	7779 ± 114	8062.3 ± 1407.4	8545.7 ± 1259.5	8574.7 ± 996.1	7898.9 ± 887.8
WR (m·min^{-1})	99 ± 4	105 ± 2	97 ± 1	89.6^{e}	95.0^{e}	95.2^{e}	87.8^{e}
SPR (m)	275 ± 42	131 ± 24	188 ± 16	247.8 ± 143.3	96.0 ± 46.1	282.8 ± 143.3	138.9 ± 85.0
HSR (m)	665 ± 71	660 ± 40	590 ± 27	520.1 ± 243.0	433.8 ± 117.2	636.9 ± 226.2	347.9 ± 61.2
Estimated LOW (m)	7012	7658	7001	7294.4	8015.9	7655.0	7412.1
ACCEL >1.0 m·s^{-2}	-	-	-	167.5 ± 34.6	149.7 ± 16.8	199.0 ± 31.8	165.0 ± 21.5
DECEL <-1.0 m·s^{-2}	-	-	-	105.5 ± 26.9	92.5 ± 13.7	122.0 ± 16.3	85.8 ± 14.9

TOTAL = total distance; WR = work rate (total distance per time played),;^{e} = estimate of WR using 90 minutes time played; SPR = sprinting distance (>5.6 m·s^{-1}); HSR = high-speed running distance >4.3 m·s^{-1}, ≤5.6 m·s^{-1}); Estimated LOW = running distance (0.0-4.3 m·s^{-1}), estimated from the means (TOTAL – SPR – HSR = LOW); ACCEL = number of accelerations (> 1.0 m·s^{-2}); DECEL = number of decelerations (< -1.0 m·s^{-2})

2.3.5 Internal indication of match load

While much focus is given to externally-evaluated match load, the use of HR monitors synced to GPS devices constitute one method of measuring internal indications of match load in team sports. Heart rate data can provide an indication of the amount of physiological work being performed by a player irrespective of externally observed match load (Carling, 2013) and is used to indicate the intensity of physical activity (Borresen & Lambert, 2008). In adult female soccer, internal match load measured by HR monitors showed no difference in average HR (159 – 164 beats per minute (bpm)) between the 1st and 2nd halves and was similar between international and domestic games in the same cohort of international players (Andersson et al., 2010). The average HR in match-play corresponded to 84 – 86% of peak HR measured during the 90-minute matches. Although a reduction in HSA and external match load was observed in later match stages at both playing standards, the reduction in external measures was not reflected in the internal measurement (Andersson et al., 2010), demonstrating the separate internally- and externally-evaluated mechanisms of match load as discussed by Carling (2013).

In high-level domestic female players, small but non-significant changes in HR were observed between 1st and 2nd half (170 -- 167 bpm) across three matches, or 86% of tested maximal HR (HR_{max}); average HR was not different between 15-minute match intervals (Krustrup et al., 2010). Similar to Andersson et al (2010), the lack of change in HR within a match did not reflect the results of post-match tests that indicated reduced physical performance due to match-play (Krustrup et al., 2010). A study of youth female soccer players (years 12.1 ± 0.9) also observed small but nonsignificant decreases in average HR from 1st to 2nd half (178 -- 174 bpm), reporting an average 87% of tested HR_{max} (Barbero-

Álvarez et al., 2008). This aligns with a study of high-level domestic female players reporting an average HR of 167 bpm, also corresponding to 87% of tested HR_{max} (Krustrup et al., 2005). Reported average HR for match-play in differing playing standards, player performance levels, and ages indicates similar intensities (86 – 87% of HR_{max}) of internal work for female soccer players. These also show HR does not significantly decrease with reductions of match load in later match stages. It has been suggested that the lack of significant decrease in HR – despite observed decreases in HSA (which is linked to aerobic capacity) – might be due to limitations in heart rate monitoring for assessing match-play intensity, as in both Andersson et al (2010) and Krustrup et al (2010), HR was not found to correlate with tested VO_{2max} (Datson et al., 2014). However, the sampling rate for HR in these studies was at 5-second intervals (Andersson et al., 2010; Krustrup et al., 2010), where by contrast, current HR monitoring integrated with GPS allows for 5 samples per second, which could impact on the HR parameters observed due to the intermittent nature of soccer. Heart rate response in adolescent female matches has not been previously reported and with the use of more recent HR monitoring devices may provide further insight into the total match load in female adolescent soccer.

2.3.6 Substitution use in soccer – effect on match load

An important factor in considering the match load of adolescent soccer is the use of substitutions, an understudied aspect of soccer (Hills et al., 2018). Players are substituted for different reasons including injury, fatigue, tactical reasons, and providing match-play time for players (Hills et al., 2018). Youth soccer rules in the FA allow for unlimited substitutions in regular league matches where substituted players can return to match-play (The English Football Association, 2017a). In cup competition matches, substitutions are limited to three players per match and return of substituted players to match-play is not permitted (The English Football Association, 2016). In regular league and friendly matches, unlimited substitutions can result in a majority of players in a team not playing an entire match. Limited substitutions in a cup match can also result in up to 6 players not completing an entire match. Both limited and unlimited substitution conditions can create large variations in time played per player. A recent review of the literature of substitutes in soccer (Hills et al., 2018) highlights that substitutes have higher work rates compared to full-match players, and that players perform greater HSA distances as substitutes compared to HSA performed when they are full-match players. These findings demonstrate differences between substitutes and full-match players with higher-intensity match loads for substitutes in a shorter space of time. However, to date, no studies have reported on the match loads of substitutes in adolescent female soccer which may be further affected by the unlimited nature of substitution rules allowing re-entry to a match.

Substitution rules in women's college soccer are similar to regular league matches for youth in the FA, allowing for players to be substituted off the pitch in the 1st or 2nd half and return to match-play in the 2nd half with the entire team available for substitutions (Favero et al., 2015). Frequent use of substitutions in women's college soccer has been shown to be for both tactical purposes and to prevent match fatigue (Favero et al., 2015). One study demonstrated how the use of substitutions in women's college soccer results in varied match-play time played per player creating a large range of observed match loads across a single soccer season, however the separate evaluation of substitutes from full-match players was not undertaken in the study (Gentles et al., 2018).

Two studies have described the separate match loads of substituted players compared with full-match players in female soccer (Trewin et al., 2017; Vescovi & Favero, 2014). In comparing the match load of early (>22.5 min time played) and late (<22.5 min time played) substitutes under limited substitution conditions and players who completed a full match in international female soccer, Trewin et al (2017) observed a higher work rate, sprint distance per minute, and high-intensity accelerations (>2.26 $m \cdot s^{-2}$) per minute in late substitutes compared to early substitutes and full-match players, along with a higher relative high-speed running distance for early substitutes compared to full-match. Vescovi and Favero (2014) compared substitutes in US women's college soccer, finding that players substituted out of a match who later returned to match-play maintained relative match load levels and that players substituted back into match-play had high work rates and higher proportions of HSA compared to full-match players, similar to findings of late substitute match loads observed in Trewin et al (2017). This suggests that additional rest during a match may have a mitigating effect on the attenuation of high-intensity match load in female soccer and thus on the onset of fatigue in response to match-play but requires further exploration.

2.4 Neuromuscular response to match-play in adolescent female soccer

2.4.1 Fatigue in match load

In soccer, fatigue has been shown to occur in later match stages which may be indicated in performance reductions seen in analysis of match loads (Mohr et al., 2005). As fatigue has been cited as a risk factor in injury (Barber-Westin & Noyes, 2017), the monitoring of fatigue onset through motion analysis may assist in injury prevention methods. In addition to understanding adolescent-specific match loads and fatigue onset in match-play, fatigue as an injury risk factor in adolescent female soccer players and methods of monitoring fatigue response to match-play should also be considered. This section of the Review of Literature seeks to inform the reader of the need to monitor fatigue onset and neuromuscular response to match-play in adolescent female soccer players in consideration of fatigue as a contributing risk factor to injury. Current understandings of the fatigue response in female soccer players to match-play are discussed in additional to methods of assessing neuromuscular response.

2.4.2 Considering injury risk in adolescent female soccer

Injury negatively impacts players in terms of costly care (Hewett et al., 2006), has long-term health impacts (Lohmander et al., 2004), and negatively impacts team performance (Hägglund et al., 2013). Concerningly, injury rates do not appear to be decreasing in youth female soccer (Khodaee et al., 2017; Le Gall et al., 2008). With injury prevention as a priority aim in soccer, sport scientists and health professionals have sought to understand the causes of injury and the associated risk factors of injury (Larruskain et al., 2018). A recent long-term epidemiology study showed that for adolescent-aged female soccer players (13 – 18 years of age), more injuries occur during matches compared to training, with younger players having a majority of injuries occur during competition (67.7%) (DiStefano et al., 2018). This trend of the majority of injuries occurring during match-play was generally reflected in other prospective studies of injury rates in adolescent soccer players (Clausen et al., 2014; Del Coso et al., 2018; Le Gall et al., 2008; Soderman et al., 2001).

In studies considering incident rates within adolescent female soccer, younger age groups appear to be more at risk of injury. In an 8-season prospective study of 119 U15 – U19 female international players, injury incidence rates were highest in U15 players and steadily decreased with increasing age to U19, with U15 players nearly twice as likely to sustain injuries as U19 players (relative risk ratio (RR): 1.7, $p < 0.05$); overall injury incidence rates were not significantly different across all 8 seasons (Le Gall et al., 2008). A single season study of 317 domestic adolescent soccer players (U14 – U18) reported a similar trend for female players, with U14 players having the highest injury rates (7.92 per 1000 h), followed by U16 (5.74 per 1000 h), and U18 (2.53 per 1000 h) (Emery et al., 2005). These trends suggest younger adolescent female soccer players, particularly players 13 – 15 years of age, are more at risk of injury.

In sports such as soccer, chronological age is how players are placed into teams and competition groups. However, in adolescence, a growth spurt occurs which can result in variations in player stature among a team with similar chronological ages, including differences in size, physique, and body composition (Buenen & Malina, 2007). This process of growth towards a mature state (adult stature) is called maturation (Buenen & Malina, 2007; Stratton & Oliver, 2014). While maturation and chronological age are interrelated, the chronological age when the adolescent spurt begins varies, usually between the ages of 11 and 14 in girls (Oliver & Rumpf, 2014). The age differences in the onset of adolescent growth spurt result in stature variations among persons in the same chronological age group in adolescence (Oliver & Rumpf, 2014). Further, maturation is associated with changes in motor performance, including a linear increase in strength in girls through the age of 15 (Buenen & Malina, 2007) which plateaus in later adolescence until full maturity (Stratton & Oliver, 2014). Maturational status is represented by peak height velocity (PHV), the maximum velocity or rate of growth in stature (Lloyd & Oliver, 2012), which generally occurs around the age of 12 in girls (Stratton & Oliver, 2014).

An increased risk of injury in soccer coincides with maturation and PHV (Rumpf & Cronin, 2012; Van Der Sluis et al., 2014). For example, the risk of anterior cruciate ligament (ACL) injury in female athletes is highest after the adolescent growth spurt (Hewett et al., 2006). This is confirmed by epidemiology data from 20 years of ACL injuries in youth showing the prevalence of severe ACL injury peaks at 15 – 16 years of age in girls (Beck et al., 2017), at an age which is post-PHV and when the rate of maturation in girls has begun to plateau. It is thought that a higher centre of mass due to increased height along with increased forces acting on joints due to increased body mass associated with adolescent growth contribute to changes in neuromuscular control (Hewett et al., 2004, 2006). This includes negatively affecting balance, coordination, and joint control in late-maturation stages in adolescent female soccer players, which results in increased injury risk (Hewett et al., 2004, 2006). Changes in neuromuscular control due to maturation suggest adolescent female soccer players are at increased risk of injury during and following PHV compared to later adolescence. This reflects the results of epidemiology studies that players 13 – 15 years of age have a higher rate of injury compared to older adolescent players. The consideration of both chronological age and maturation in adolescent female soccer would be beneficial to understanding both injury risk factors and sport performance.

2.4.2.1 Risk factors in noncontact injury

The incidence of noncontact injuries to the lower limb in adolescent female soccer is high (DiStefano et al., 2018). With the understanding that, in the absence of outside forces contributing to injury, noncontact injuries incidences might be prevented (Gabbett, 2010), the mechanisms and risk factors of noncontact injuries have received much scrutiny. One method of framing injury risk factors biomechanically is to categorise risk factors as environmental, anatomical, hormonal, or neuromuscular (Griffin et al., 2006). Briefly, 1) environmental factors pertain to external factors such as weather, playing surface, and footwear; 2) anatomical factors include mechanical alignment of joints and muscles (i.e. the Q angle or foot pronation), body mass, and bone, muscle, and ligament properties; 3) hormonal factors include the potential effect of sex hormones on collagen synthesis in ligaments and therefore the effects of the female menstrual cycle on ligaments as well as the effects of the menstrual cycle on joint laxity; and 4) neuromuscular factors which are grouped into altered movement patterns, altered activation patterns, and inadequate muscle stiffness (Griffin et al., 2006).

Risk factors and injury mechanisms may interact, as injuries are multifactorial (Bahr & Krosshaug, 2005); however, to prevent injury, modifiable risk factors are considered (Alentorn-Geli et al., 2009). Most environmental, anatomical, and hormonal risk factors could be considered non-modifiable, with exceptions such as choice of footwear and potential modification of body mass and muscle properties. In female athletes in particular, the menstrual cycle and related hormones may have an effect on performance and injury risk with potential modification through oral contraception (Datson et al., 2014). While this female-specific factor has received attention within the literature, findings of effects are unclear or limited (Datson et al., 2014).

The modification of neuromuscular factors, by contrast, are potentially the most modifiable (Hewett et al., 2006). One neuromuscular risk factor that may contribute to altered movement and activation patterns and muscle stiffness is fatigue (Hewett et al., 2006; Padua et al., 2006). Fatigue has been cited as a risk factor in injury due to negative effects on dynamic muscle control, knee and hip kinetics and kinematics, and ground reaction forces during landing in the presence of fatigue (Barber-Westin & Noyes, 2017). Fatigue is cited as a potential contributing risk factor in ACL injury (Griffin et al., 2006), hamstring injury in soccer (Navarro Cabello et al., 2015), and ankle sprains (de Noronha et al., 2019). Understanding and recognising the development of fatigue in adolescent female soccer could benefit injury prevention methods.

2.4.2.2 Match load and injury risk

The presence of fatigue in injury can be inferred in match-play through a combination of epidemiological and match performance data. Analysis from 9 years of data from the High School Reporting Information Online injury surveillance system showed that the majority of injuries in high school female soccer occur in later stages of training (1 – 2 hours into practice) (55.9%) and in the 2nd half of match-play (63.2%) (Khodaee et al., 2017). In multi-season prospective studies of professional male adult and youth soccer, the occurrence of injury was reported to be higher at the end of the 1st half and higher in the 2nd half (Ekstrand et al., 2011; Hawkins & Fuller, 1999). A recent systematic review in team field sports found that ankle sprains were more likely to occur in the second half and at the end of both match halves (de Noronha et al., 2019). Additionally, a large five-season prospective study with 41 academy male soccer teams found that the risk of thigh muscle injuries was highest from the latter half of the 1st half through to the end of the match (Cloke et al., 2012). Although further epidemiology research is necessary to understand the timings of injuries within adolescent female soccer, studies suggest that injury in soccer is more likely to occur in later match stages.

Injuries in later match stages appear to be concurrent with the phenomenon of decreased performance in later match stages, which decrease is cited as occurring due to fatigue (Mohr et al., 2003, 2005). Studies quantifying match load in female soccer demonstrate declining performance in later match stages, an indication of fatigue development within a match and a phenomenon commonly reported in the literature (Andersson et al., 2010; Datson et al., 2017; Hewitt et al., 2014; Mara et al., 2017a; Mohr et al., 2008; Ramos et al., 2017; Strauss et al., 2019; Vescovi, 2014). Studies show declines in high-speed running — a key part of match performance — occur in both international and domestic female soccer (Andersson et al., 2010; Mohr et al., 2008). Declines in performance have also been observed in U16 and U17 female soccer, with reductions in total distance from 1st to 2nd half (Vescovi, 2014). Epidemiology data demonstrating injuries occurring in the 2nd half of matches and the corresponding occurrence of reduced match performance in the 2nd half in female soccer suggest that fatigue can be a contributing risk factor to injury. An understanding of acute fatigue onset due to match-play could be beneficial to developing methods to decrease injury risk and tracking of match load and decreases in performance during match-play may provide further insight into assessing player injury risk.

2.4.3 Neuromuscular response in female soccer

2.4.3.1 Acute neuromuscular fatigue

Fatigue is a complex phenomenon that has been the basis of much inquiry including several literature reviews and meta-analyses in team sports (Knicker et al., 2011; Waldron & Highton, 2014) and in soccer (Mohr et al., 2005; Nédélec et al., 2012; Reilly et al., 2008; Silva et al., 2017). Fatigue can be defined as an impairment of performance induced by exercise (Knicker et al., 2011). Although it is a multifaceted phenomenon, the study of physical performance declinations arising from fatigue has focused on reductions in muscle power output (Mohr et al., 2005; Nédélec et al., 2012; Rampinini et al., 2011; Waldron & Highton, 2014).

Reductions in performance can occur as a result of peripheral and/or central fatigue. Peripheral fatigue occurs distally within the musculature and is related to physiological processes (Waldron & Highton, 2014), resulting in reduced muscle cell force (Knicker et al., 2011). Central fatigue involves central motor drive to recruit motor units (Waldron &

Highton, 2014) by providing neural input to neuromuscular junctions (Silva et al., 2017). The decrease of central motor drive causes a reduction in voluntary muscular activation (Gandevia, 2001). Peripheral and central fatigue processes are separate as evidenced by differing recovery times of central and peripheral fatigue indicators: central fatigue markers (motor output) are observed to be recovered 48 hours post-exercise, whereas peripheral indicators (physiological markers) are still present 72 hours post-exercise (Silva et al., 2017). However, both peripheral and central fatigue result in reduced muscle power output. Under fatigued conditions, peripheral fatigue and biochemical changes within a muscle provide feedback to intramuscular receptors, which influences the central nervous system (CNS) by eliciting reductions in motor unit drive, contributing to reduced force production (Gandevia, 2001). It has been suggested that reductions of central motor drive to peripheral musculature are to maintain performance and restrict the development of peripheral fatigue (Amann, 2011; Marshall et al., 2014; Sidhu et al., 2013). The interaction between central and peripheral fatigue that causes decreased function and output of the neuromuscular system is defined as neuromuscular fatigue (NMF) (Bigland-Ritchie & Woods, 1984; Boyas & Guével, 2011; Silva et al., 2017).

In soccer, acute NMF occurs both temporarily, where fatigue is induced for short periods after intense bouts of match-play, and over the course of match-play, where fatigue occurs towards the end of a match (Mohr et al., 2005). Fatigue also has residual effects where reduced performance and fatigue markers can still be observed more than 72 hours post-match (Silva et al., 2017). Chronic or accumulated fatigue can occur in the absence of recovery from acute NMF, when players must reperform shortly after preceding exercise bouts, such as during congested match schedules (Nédélec et al., 2012). It has been suggested that different fatiguing mechanisms act at different stages within a match such as the taxing of anaerobic systems during intense match periods, resulting in temporary fatigue lasting for a short period of match-play; and glycogen depletion in muscle fibres occurring in later match stages resulting in decreased running performance (Knicker et al., 2011; Mohr et al., 2005). These examples demonstrate that the mechanism inducing fatigue and its observed effects are directly related to the specific task performed (Hunter et al., 2004; Waldron & Highton, 2014), i.e. temporary fatigue is induced by short and intense periods of movement resulting in overtaxed anaerobic systems, and acute fatigue experienced in later match stages is induced by constant movement at intermittent intensities throughout a match resulting in muscle glycogen depletion. However, it has been acknowledged that these mechanisms overlap or act in combination to reduce performance (Knicker et al., 2011; Waldron & Highton, 2014). This complexity of overlapping mechanisms and simultaneous effects presents challenges when studying NMF in match-play.

2.4.3.2 Measures of fatigue and neuromuscular response in female soccer

In defining fatigue as a decline in performance induced by exercise, Knicker et al (2011) present a paradigm for biomechanically assessing fatigue and its effects (Figure 2.3). Performance decrements can be assessed on three levels (Knicker et al., 2011): (1) reduction in power output of specific muscles which results in (2) reduced exercise performance. Within the context of soccer, reduced muscle output in lower extremity muscles would result in a decreased ability to perform running tasks such as sprints during a match. This in turn would result in (3) reduced sport performance, as high-speed running is an indicator of player performance in soccer (Mohr et al., 2003). These sport performance reductions can be monitored via motion analysis such as with GPS (Carling et al., 2008). Muscular performance is assessed through tests of muscle-specific power, velocity, or force; because power = force x velocity, (Gandevia, 2001), these tests can be considered direct measures of fatigue

(Knicker et al., 2011). Other biomechanical, physiological, or exercise assessments provide only indications of the occurrence of NMF through observing performance decrements (i.e. measures of neuromuscular response) (Knicker et al., 2011).

In addition to biomechanical muscular assessment, biochemical responses to exercise are used to assess muscle damage (Thorpe et al., 2017). For example, tests for creatine kinase (CK) in the blood plasma level — a by-product of muscle metabolism — are the most commonly used in soccer to assess biochemical response to match-play (Silva et al., 2017; Viru & Viru, 2001). Markers of muscle damage provide an indication of NMF, as muscle damage may relate to decreased muscle force production (Raastad et al., 2003). Various other tests of physiological responses have been utilised in soccer, generally including assessments of oxidative stress or inflammation response (Silva et al., 2017), although these are outside the scope of this literature review and have not been conducted in research on match-play in adolescent female soccer.

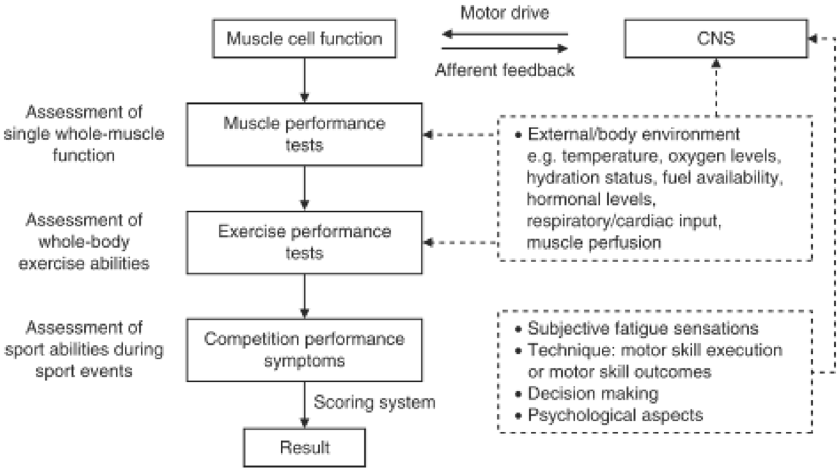


Figure 2.3 A paradigm for biomechanically assessing NMF within sports, including potential environmental, psychological, and physiological factors that can influence performance (dotted boxes). Indications of the presence of NMF can be observed on three levels: muscular performance, exercise performance, and sporting performance. Fatigue can be directly measured only with muscular performance tests. Adapted from “Interactive Processes Link the Multiple Symptoms of Fatigue in Sport Competition,” by A. Knicker, I. Renshaw, A. Oldham, and S. Cairns, 2011, *Sports Medicine*, 41(4), p. 309.

It has been noted that methods to collect muscular performance and biochemical data for the purposes of monitoring fatigue from match-play can be cost-prohibitive in terms of equipment and logistically burdensome for teams and staff (Carling et al., 2018; Thorpe et al., 2017), which may especially apply in women’s soccer and for youth teams. Instead, exercise assessments of performance as defined in the NMF assessment paradigm are frequently utilised. Exercise assessments of performance involve multiple muscle groups, further testing coordination, and thus a CNS influence; these measures of neuromuscular response are usually performed pre- and post-match or training (Knicker et al., 2011). Exercise assessments include performance tests such as sprint, aerobic fitness, and jumping tests (Twist & Highton, 2013). Jumping tests are commonly used as they result in minimal additional fatigue compared to sprint or aerobic tests (Twist & Highton, 2013), which are not practical after fatiguing exercise in team sports (Thorpe et al., 2017).

In team sports, jumping tests are commonly used exercise assessments due to specifically testing lower limb function and easy implementation (Hogarth et al., 2014), especially in a team setting with large numbers. Rebound jumping (i.e. hopping) tests incorporate the stretch-shortening cycle (SSC) (Hogarth et al., 2014) — a muscular function where a preactivated muscle is stretched before being contracted, resulting in a fast eccentric to concentric transition present in hopping and running — which is negatively affected by neuromuscular fatigue through changes in leg stiffness (Flanagan & Comyns, 2008; Komi, 2000). Leg stiffness describes the vertical stiffness of the leg as a spring-mass model, where the sum of the tendons, muscles, cartilage, bones, and ligaments act as a spring to move the mass of the body (Butler et al., 2003; McMahon & Cheng, 1990). Increase in lower leg stiffness results in increased running speed and decreased energy cost of running (Butler et al., 2003), thus playing a role in sport performance in soccer. Reduced leg stiffness in the presence of fatigue decreases force output (Komi, 2000) and indicates negative changes in neuromuscular control (De Ste Croix et al., 2016). The known interaction of leg stiffness and the SSC, and negative impacts of fatigue on both, allow for tests of leg stiffness and SSC function to measure neuromuscular response.

Hopping tests use measures of flight time and contact time during hops to calculate leg stiffness (Dalleau et al., 2004). Similarly, flight time and contact time can be used to calculate the reactive strength index (RSI), a ratio of jump height and contact time that provides a measure of SSC function (Flanagan & Comyns, 2008). Tests of leg stiffness from a submaximal hopping test have been shown to be reliable in youth and adolescent female soccer players (De Ste Croix et al., 2016; Lloyd et al., 2009). Tests of RSI have also been shown to be reliable in athletes (Eamonn P. Flanagan et al., 2008). Vertical jump tests such as the countermovement jump (CMJ) test are functional measures of lower limb power (Datson et al., 2014; Stølen et al., 2005) that can be assessed using flight time measures and subsequent calculation of jump height. CMJ has been shown to be a reliable indicator of lower limb power in athletes (Cormack et al., 2008) and an indicator of neuromuscular status to monitor fatigue (Claudino et al., 2017). Neuromuscular response in lower limb function can be assessed in laboratory settings using force plates and 3D kinematic assessments, however, valid and reliable jumping and hopping tests that utilise mobile contact mats provide field-based measures of lower limb function in a cost-effective manner (Dalleau et al., 2004). Field-based tests of CMJ, maximal hop, and submaximal hop using mobile contact mats allow for neuromuscular response to be practically and cost-effectively measured within match-play settings.

2.4.3.3 Neuromuscular response in female soccer

Several studies of evaluating NMF and neuromuscular response to match-play or match simulation have been undertaken in adult female soccer (Andersson et al., 2008; Bendiksen et al., 2012, 2013; Delextrat et al., 2013; Gravina et al., 2011; Hoffman et al., 2003; Krustrup et al., 2010; Souglis et al., 2015). While tests from match-like simulations provide controlled conditions that allow for the study of specific measures or symptoms of NMF (Knicker et al., 2011), it is argued that these tests might not accurately represent fatigue that occurs in soccer match-play as simulations cannot account for the unpredictable nature of match-play (Nédélec et al., 2012; Silva et al., 2017) and do not take into account positional differences in match load. In general, studies tend to be conducted with small sample sizes due to team sizes and logistical constraints (Carling et al., 2018; Thorpe et al., 2017). However, findings from adult female soccer reflect those described in a recent meta-analysis of fatigue measures in male and female soccer demonstrating patterns of NMF and neuromuscular responses due to match-play (Silva et al., 2017).

2.4.3.3.1 Muscular assessments of fatigue

Two studies evaluated knee torque under different conditions (Andersson et al., 2008; Delextrat et al., 2013). Delextrat et al (2013) tested the eccentric hamstring (H) and concentric quadriceps (Q) torque in both legs of 14 amateur players before and after a Loughborough Intermittent Shuttle Test modified to include a shooting drill; the researchers reported a 14.1% decrease in the functional H:Q ratio in players' dominant leg and 8.0% decrease in player's non-dominant leg. The decreases observed were due to significant decreases in peak eccentric torque of the hamstrings (8 – 17%, $p < 0.05$), whereas peak concentric torque of the quadriceps was not significantly different pre- to post-match. In 2 friendly matches separated by 72 hours, Andersson et al (2008) conducted pre- and post-match tests of isokinetic concentric knee extension and flexion on players' dominant leg with 17 professional domestic players. Averages from both matches showed a 7% decrease in peak torque flexion and 5% decrease in peak torque extension from pre- to post-match. Where Delextrat et al (2013) found no significant change in concentric quadriceps torque, Andersson et al (2008) observed a 5% decrease. As the simulation used in Delextrat et al (2013) is a shuttle test, there would be a lack of intense decelerations or changes of direction, both movements which are performed primarily through eccentric quadriceps and gastrocnemius contractions (Hewit et al., 2011); a lack of these movements in the simulation might explain the lack of fatiguing effect in the quadriceps. Both studies observed a decrease in hamstring group strength under differing conditions (concentric v eccentric tests). Decreased hamstring strength due to fatigue is a concern due to the role of hamstrings as protagonist to the ACL to protect the ligament (Hewett et al., 2006) and for potential hamstring strains as previously discussed. Overall, both studies observed a significant decrease in lower limb muscle output, demonstrating the occurrence of NMF in female soccer players in response to prolonged intermittent exercise.

Data on NMF in adolescent female soccer is similarly limited. A study of U13, U15, and U17 female players (U13: n = 14, 12.1 ± 0.5 years; U15: n = 9, 13.9 ± 0.6 years; U17: n = 13, 15.8 ± 0.5 years) assessed electromechanical delay (EMD) in the hamstrings and posterior calf muscle groups. Tests for EMD were conducted before and after the soccer-specific aerobic field test ($SAFT^{90}$) adjusted for times mirroring age-specific match lengths (75, 80, and 90 min, respectively) (De Ste Croix et al., 2015). EMD was tested on eccentric knee flexion on the player's dominant leg. For all groups, EMD was significantly increased post-exercise (58.4%, $p = 0.001$) after the match simulation, representing a delay in force generation and the presence of NMF. Importantly, EMD in U13 players was significantly longer than U15 (15.8% longer, $p = 0.011$) and U17 players (24.1% longer, $p = 0.021$) and that these age-specific differences were observed both pre- and post-exercise; no significant differences were observed between U15 and U17 age groups (De Ste Croix et al., 2015). Research has shown a relationship between EMD and leg stiffness, where age-related increases in leg stiffness were correlated ($r < -0.83$) with decreases in EMD (Waugh et al., 2013). This reflects another study that observed increased leg stiffness with increased age in male youths (Lloyd et al., 2012). These findings suggest a maturational factor in differences in EMD and neuromuscular control (De Ste Croix et al., 2015), both processes of which are affected by fatigue. This may relate to the observed effect of maturation on injury prevalence discussed previously (Rumpf & Cronin, 2012; Van Der Sluis et al., 2014). Findings also suggest the development of fatigue in response to match-play in adolescent female soccer.

A maturational effect was also observed in a study of functional H:Q ratio of the dominant leg in U13, U15, and U17 female soccer players. Players were tested pre- and post-match simulation (SAFT^{90}) conducted for times mirroring age-specific match lengths (75, 80, and 90 min, respectively) (De Ste Croix et al., 2018). Probabilistic inference of pre- to post-exercise differences in H:Q ratio were unclear in U13 players, likely detrimental in H:Q ratio in U15 players, and very likely beneficial in H:Q ratio in U17 players. De Ste Croix et al (2018) suggest a fatigue resistance that may develop in later adolescence alongside a potential training effect may explain the beneficial increases in H:Q ratio in U17 players. This coincides with increases in leg stiffness (potential positive development in response to exercise) and decreases in EMD response in older age groups compared to younger age groups as previously discussed. Comparatively, U15 players appear to have decreased neuromuscular control in the presence of fatigue presented as decreased eccentric hamstring torque, which aligns with decreased eccentric hamstring torque observed in Delextrat et al (2013). The decreased hamstring strength observed in U15 players represents an increased risk of ACL injury, which in female athletes is highest after the adolescent growth spurt (De Ste Croix et al., 2018; Hewett et al., 2006). As decreased hamstring strength due to fatigue is a risk factor in ACL injury (Hewett et al., 2006), these findings reflect a maturational effect on neuromuscular fatigue response and injury risk.

2.4.3.3.2 Biochemical responses to match-play

Other studies have conducted biochemical tests of neuromuscular response, focussing on blood sample tests (Andersson et al., 2008; Gravina et al., 2011; Souglis et al., 2015). Reports from competitive match-play in adult female soccer observed 62 – 116% increases in plasma CK levels from pre- to post-match (Andersson et al., 2008; Gravina et al., 2011;

Souglis et al., 2015), demonstrating the presence of muscle damage in response to match-play. A single study has reported physiological responses to match-play in adolescent female soccer (Hughes et al., 2018): U13, U15, and U17 female players (U13: n = 11, 12.9 ± 0.63 years, U15: n = 10, 13.82 ± 0.62 years, U17: n = 12, 15.78 ± 0.35 years) were assessed for CK levels prior to a match and at 80 hours post-match (Hughes et al., 2018). CK levels were statistically significantly increased at 80 hours post-match from pre-match levels for all three age groups, with a small effect size for U15 players (ES = 0.45) and large effect sizes for U13 and U17 players (ES = 0.72 and 1.59, respectively) (Hughes et al., 2018). This represents the presence of muscle damage as a result of match-play. Although post-match tests of CK were not conducted immediately after match-play, Andersson et al (2008) reported that plasma CK levels in adult female players were statistically significantly elevated immediately post-match compared to pre-match tests, and were still statistically significantly elevated compared to pre-match testing at 45 hours post-match (Andersson et al., 2008). Findings demonstrate that muscle damage is present in response to competitive match-play in adolescent and adult female soccer players, which indicates the presence of fatigue, as induced muscle damage may impact muscle force production (Raastad et al., 2003).

2.4.3.3.3 Exercise assessments of neuromuscular responses to match-play

Additionally, several studies conducted exercise performance assessments, including sprint tests (Andersson et al., 2008; Bendiksen et al., 2012, 2013; Krustrup et al., 2010) and CMJ tests (Andersson et al., 2008; Hoffman et al., 2003; Krustrup et al., 2010). Sprint test types varied, including a 20 m sprint test pre- and post-match (H. Andersson et al., 2008), 2 x 20 m sprints tested at the start and end of the Copenhagen Soccer Test match-simulation (Bendiksen et al., 2012, 2013), and a 3 x 30 m repeated sprint test pre- and post-match (Krustrup et al., 2010). In all studies sprint speed declined (3 – 7%) from pre- to post-match.

The studies that included CMJ had differing results. In Andersson et al (2008), CMJ height was measured pre- and post-match for two matches separated by 72 hours; CMJ height decreased significantly (4.4%) at the end of the first match and was still significantly decreased (3.6%) compared to baseline at pre-match testing prior to the second match. Further declines were observed after the second match (1.9%), though significance was not reported. By contrast, Krustrup et al (2010) used the same test procedures as Andersson et al (2008) for the CMJ but found no significant difference pre- to post-match in a similarly high level of domestic players.

A third study where CMJ tests were performed pre- and post-match using a position transducer also found no difference in CMJ measures of power immediately post-match; however, decrements were observed 24 hours post-match (Hoffman et al., 2003). This study included 19 substitutes and starters in a women's college match. Although CMJ measures were decreased at 24 hours post-match, starters had significantly greater declines compared to substitutes, suggesting a time interaction of match-play and fatigue response. Starters played significantly more time (56.5 ± 14.0 min) compared to substitutes (29.0 ± 13.9 min), although a lack of players completing the entire match has been suggested as a reason for lack of expected decrement in CMJ performance (Hoffman et al., 2003). This aligns with the Delextrat et al (2013) observation of no decrement to concentric peak torque of the quadriceps, as the CMJ has a large concentric quadriceps component (Finni Juutinen et al., 2000). However, lack of time played may not account for the differences of CMJ with similarly matched competition level in competitive match play (Andersson et al., 2008; Krustrup et al., 2010). Where studies in adult female soccer showed decrements in post-match speed production, results of CMJ tests have conflicting results, similar to results in men's soccer (Silva et al., 2017).

A recent study utilised a CMJ test for pre- and post-exercise testing in adolescent female soccer players (n = 15, 13.1 ± 1.4 years of age); the authors observed increased force production at the end of the 90-minute SAFT^{90} match simulation compared to pre-exercise testing (Wright et al., 2017). Although players reported feelings of fatigue and the SAFT^{90} was 10 minutes longer than a normal match for this age group, the flight time to contraction time ratio of the jump trivially decreased in conjunction with increased force production. These findings conflict with previous studies including decreased post-match CMJ performance (Andersson et al., 2008) or CMJ performance that was not significantly altered by match-play (Hoffman et al., 2003; Krustrup et al., 2010). It is possible the observed increase in CMJ may reflect a maturation effect as observed in adolescent post-exercise EMD noted in De Ste Croix et al (2015). Similarly, a maturation effect was also observed in leg stiffness tests conducted pre- and post-exercise testing using the SAFT^{90} in U13, U15, and U17 players (U13: n = 14, 12.1 ± 0.5 years; U15: n = 9, 13.9 ± 0.6 years; U17: n = 13, 15.8 ± 0.5 years) (De Ste Croix et al., 2016), where leg stiffness response to fatigue was -4.9% in U13, +1.5% in U15, and +12.3% in U17 groups, with probabilistic inference ratings of possibly negative, unclear, and very likely positive, respectively. Most participants (> 70%) in the U13 group demonstrated decreased stiffness, with mixed results in the U15 group (4 increased, 5 decreased), and all U17 players increasing leg stiffness from pre- to post-exercise. These findings may reflect previous findings of beneficial fatigue response post-exercise in the same group of players, with observed increases in H:Q ratio in U17 players (De Ste Croix et al., 2018); however, parallels with U13 and U15 players are not clear. Leg stiffness as a measure of SSC function and H:Q ratio as a measure of muscular torque make these comparisons cautious. Results of exercise tests in response to fatigue in adolescent female soccer players warrant further study.

Measures and symptoms of NMF demonstrate altered neuromuscular control of the lower limb musculature in response to match-play and match simulations. A summary of the results of neuromuscular response tests in adolescent female players is in Table 2.4. In adolescent female soccer players, markers of muscle damage were observed in all three age groups post-match (Hughes et al., 2018). There is also a maturational effect on fatigue responses (De Ste Croix et al., 2018; De Ste Croix et al., 2015, 2016). Although increases in EMD were observed in all three adolescent age groups, H:Q ratios observed negative changes in U15 players and positive changes in U17 players in response to exercise. Leg stiffness decreased in U13 players and increased in U17 players. CMJ tests in U15 players measured increases in relative force production in response to exercise (Wright et al., 2017). Altered control of lower limb musculature due to the presence of fatigue represent the potential presence of elevated injury risk, although a protective effect in response to fatigue may be present in older adolescent players. Further evaluation of neuromuscular fatigue responses in adolescent female soccer is warranted.

Table 2.4 Summary of inferential results of neuromuscular response tests (NMRT) in adolescent female soccer players (De Ste Croix et al., 2018; De Ste Croix et al., 2015, 2016; Hughes et al., 2018; Wright et al., 2017)

NMRT (reference)	U13	U15	U17
CK (Hughes et al, 2018)	↑	↑	↑
EMD (De Ste Croix et al, 2015)	↑	↑	↑
H:Q ratio (De Ste Croix et al, 2018)	unclear	↓	↑
Leg stiffness (De Ste Croix et al, 2016)	↓	unclear	↑
CMJ (Wright et al, 2017)	-	↑	-

2.4.3.3.4 Neuromuscular responses and fatigue measures linked to physical match load

Muscular assessments of fatigue in response to match-play and match simulation reviewed in the previous section suggest that physical match load affects NMF. Additionally, variations in match load between players may affect neuromuscular response. In comparing starters and substitute players in a women’s college soccer match, CMJ test results suggested that players with more time played (starters) demonstrated a greater fatigue response (Hoffman et al., 2003). Similarly, a decrease in H:Q ratio was observed in U15 players compared to an increase in H:Q ratio in U17 players after the SAFT^{90} (De Ste Croix et al., 2018); a potential factor for this difference might lie in different work rates, as U15 players completed similar average distances to U17 players (10,525 v 10,590 m) in 10 fewer minutes (80 v 90 min) signifying a higher work rate in U15 players which is likely more fatiguing. These suggest that higher match loads may elicit a greater neuromuscular response.

As discussed previously, fatigue is directly related to the specific task performed with intensity of exercise and muscle group involvement affecting fatigue onset (Hunter et al., 2004; Waldron & Highton, 2014). Neuromuscular responses and measures of fatigue as a result of soccer match-play focus on the lower limb as primary movers in soccer. Specific tasks of lower limb muscle groups vary during match-play: for example, powerful concentric quadricep contractions are involved in the initiation of movement in soccer, including jumping, kicking the ball, or when accelerating or changing direction (Delextrat et al., 2013). During running, hamstrings contract eccentrically to decelerate the forward motion of the lower limb before foot contact in running gait (Williams, 1985). The hamstrings also eccentrically act to assist the ACL in stabilising the knee in soccer tasks such as jumping, sprinting, and kicking (Draganich & Vahey, 1990; Li et al., 1999). During deceleration, the quadriceps and gastrocnemius muscles contract eccentrically, absorbing and dispersing force impact (Hewit et al., 2011). It has been suggested that repeated rapid decelerations may contribute to decreased sprint performance and fatigue due to repeated high loading of eccentric contractions (Lakomy & Haydon, 2004). Eccentric contractions, as utilised in running and deceleration, are associated with muscle damage (Proske & Morgan, 2001), which may impact muscle force production and NMF onset (Raastad et al., 2003). Further, it has been suggested that the energy costs of acceleration and deceleration are higher than running at a constant speed (di Prampero, 2005; Osgnach et al., 2010).

As soccer is an intermittent sport with bouts of high-intensity work, including accelerations, decelerations, and changes of direction (Reilly, 1997), eccentric work by the hamstrings and quadriceps is frequent. Muscular assessment of fatigue is not practical during match-play to quantify the NMF effects of soccer-specific tasks. However, sports performance assessment through motion analysis techniques allows for quantification of soccer-specific tasks (Carling et al., 2008) such as running, sprinting, acceleration, and deceleration that have eccentric components and are high in metabolic costs and therefore might contribute to fatigue onset. In conjunction with findings that time played – and the specific tasks of soccer match load completed within that time – may affect neuromuscular fatigue response in female soccer players and observed performance decrements into the second half of match play, the evaluation of physical match load and concurrent neuromuscular response testing might provide additional insight into the development of fatigue during match-play in adolescent female soccer.

2.5 Summary

Understanding match loads are important to informing training programmes (Datson et al., 2017; Reilly, 2005) yet to date there are only two studies expounding on match loads in female adolescent soccer match-play (Ramos et al., 2019; Vescovi, 2014), one of which focuses on international-level players. There is, therefore, a dearth of information on female adolescent match loads including at non-international levels; more data would be useful to adequately inform training programmes. Importantly, previous studies did not include observations of substitute match load, which is a key component of youth match-play due to unlimited substitution rules in non-cup competition. Limited studies on the match load of substitutes in adult soccer have shown that substitute match load significantly differs from match load of full-match players (Hills et al., 2018). However, unlimited substitutions in youth soccer – with players re-entering the field of play during a game – may have different roles compared to limited substitutions in adult soccer. Further, the interaction and impact of playing position and substitutions has not been assessed in female soccer. Greater understanding of both full-match and substitute player match load in adolescent female soccer including positional differences would be beneficial to inform training, assess performance, and monitor fatigue onset.

Match loads are used to assess the onset of fatigue during match-play (Carling et al., 2008) with the aim to minimise negative outcomes from match-play such as injury (Whitehead et al., 2018). By utilising speed thresholds to analyse match load, player performance can be assessed along with the occurrence of fatigue onset indicated in declining performance parameters. While performance decline in later match stages has been noted in several studies in adult female soccer (Andersson et al., 2010; Datson et al., 2017; Hewitt et al., 2014; Mara et al., 2017a; Mohr et al., 2008; Ramos et al., 2017; Strauss et al., 2019; Vescovi, 2014), only one study has assessed match load from both match halves in adolescent female soccer (Vescovi, 2014), which observed performance declines in U16 and U17 players. Between-half changes were unclear in U15 players. Monitoring of fatigue onset by assessing declines in match performance may assist in injury prevention methods, as fatigue has been cited as a risk factor in injury (Barber-Westin & Noyes, 2017). In adolescent female soccer players, injury occurs more frequently during match-play (DiStefano et al., 2018) and, within match-play, in the 2nd half (Khodaee et al., 2017) when declines in sports performance are often observed (Mohr et al., 2003, 2005). Further understanding of declines in adolescent female match-play through analysis of match load would assist in assessing fatigue occurrence in this age group with an outlook to injury prevention.

To determine match loads, speed thresholds are used with GPS to sort and analyse match-play, with importance placed on assessment of high-speed running due to the importance of HSA to match performance (Dwyer & Gabbett, 2012; Mohr et al., 2003) and to the study of fatigue onset in match-play (Mohr et al., 2003, 2005). However, it is not clear whether sprint-speed thresholds previously used to assess female soccer match-play are appropriate for adolescent female soccer under the age of 16. One recommended sprint-speed threshold for female soccer players utilised in the limited studies of adolescent female players is based on MSS from adult female players at or near a professional level (Bradley & Vescovi, 2015; Vescovi, 2012b). Sprint speed has been shown to increase with chronological age, with a plateau occurring around 15 – 16 years of age, with smaller increases in sprint speed observed into adulthood (Vescovi et al., 2011). While the recommended sprint-speed threshold for female players may reasonably apply to players ≥16 years of age, it is not clear if this may apply to younger players in U16 cohorts. Sprint speed tests in adolescent female soccer have shown that sprint speed may vary between adolescent age groups (Datson, 2016) and between players of differing performance standards (Hoare & Warr, 2000). Therefore, it is important to assess maximal sprint speed in U16 adolescent players to determine if the recommended sprint-speed threshold in current use may apply to younger female players so as to more accurately assess match load.

However, analysing match loads by speed measures has been shown to underestimate other low-speed, high-intensity movement (Varley & Aughey, 2013). To account for such movement in match load, it is important to include accelerations and decelerations in analysis (Dwyer & Gabbett, 2012). Accelerations and decelerations have been shown to have high metabolic costs (di Prampero, 2005; Osgnach et al., 2010) and the frequency of these efforts has been linked to decline in neuromuscular performance (Nedelec et al., 2014). Decline in neuromuscular performance due to acceleration and deceleration may be linked to the eccentric contractions of the hamstrings and quadriceps. Repetitive eccentric contractions have been associated with muscle damage (Proske & Morgan, 2001) potentially impacting muscle force production and fatigue onset (Lakomy & Haydon, 2004; Raastad et al., 2003). While accelerations and decelerations in match-play have been studied in adult female soccer, particularly at international level (Mara et al., 2017b; Meylan et al., 2017; Ramos et al., 2019; Trewin et al., 2018b), only one study has included acceleration and deceleration for adolescent players (Ramos et al., 2019).

Because match-play is subject to variations due to the influence of external match factors (Trewin et al., 2018b), relying solely on changes in match performance may not provide a complete understanding of fatigue onset. It is important to separately assess neuromuscular response to match-play as an indication of fatigue. As highlighted in this literature review, direct measures of fatigue have shown varying responses to simulated match-play, including increased electromechanical delay (De Ste Croix et al., 2015) and altered neuromuscular control in the lower limb post-exercise (De Ste Croix et al., 2018) in adolescent female players. However, muscular tests that are direct measurements of fatigue require equipment and logistics that are cost-prohibitive (Carling et al., 2018; Thorpe et al., 2017). Instead, exercise performance tests may be used to assess neuromuscular response, including countermovement jump tests (Claudino et al., 2017), the maximal hop test for RSI, and the submaximal hop test for leg stiffness (Lloyd et al., 2009). In previous studies of adolescent female players, neuromuscular responses to simulated match-play varied, including increases in CMJ performance in U15 players (Wright et al., 2017) and altered leg stiffness in adolescent players with a maturation effect (De Ste Croix et al., 2016). However, evaluations of neuromuscular response have not been conducted in response to regular match-play and would be beneficial to further understanding fatigue onset and injury risk.

CHAPTER 3

General Methods

3.1. General Methods

3.1.1 Ethical approval and participant consent

The University of Gloucestershire Research Ethics Committee evaluated and approved the protocols in these studies. The heads of the Regional Talent Club and team coaches were informed of all testing protocols and consented to testing during training and matches. All participants were under the age of 18. After being provided an information letter with details of the study, each participant and their parent or guardian gave written consent for the participant’s anonymised data to be used in the study. All data were stored and processed in accordance with the General Data Protection Regulation (GDPR).

3.1.2 Participants

Participants in each study were young healthy female soccer players from U16 teams. Participants were deemed fit to take part in the study by their team medical staff and coaches. Participants were excluded from testing if they were injured, not fully participating in all team activities, using ergonomic aids, or were being treated for any medical concerns by team medical staff. Participants that did not complete a warm up prior to testing or were unable to complete the match due to injury were also excluded.

In Study 1, four U16s teams participated: three teams were designated Regional Talent Clubs (RTC) by the English Football Association (FA) and one team was an FA Charter Standard County League team. For Studies 2 and 3, two U16s teams participated and were designated RTCs. In Studies 2 and 3, only match-play of participants in outfield positions were recorded; goalkeepers were excluded from the study due to the specific nature of their position. Participant match-play was included in analysis if a participant completed 10 or more minutes of a match. Participants who completed 75 or more minutes in an 80-minute match were considered to have played a full match.

Participants from RTCs took part in training twice a week for two hours per training session and one hour of planned home or gym-based strength and conditioning. Participants from the FA Charter Standard County League team trained twice per week for one hour per training session. All teams participated in one match per week on Saturdays during the regular season from September to May. From Studies 2 and 3, ten participants additionally trained with their national teams at various points in the season, 14 participants took part in at least one other sport on an average of 1.25 hours per week, and all participants had formal physical education classes at school an average of 3 hours per week. Participants in Studies 2 and 3 had an average football training age of 9 (± 2.5) years. Average training age was not taken in Study 1.

3.1.3 Anthropometry

Tables 3.1 and 3.2 show the anthropometric characteristics of the participants in each study. In Study 1, body mass and stature were taken as described in Section 3.1.3.1 (Body mass) and 3.1.3.2 (Stature). In Studies 2 and 3, body mass and stature were also taken as described in Section 3.1.3.1 (Body mass) and 3.1.3.2 (Stature). In Study 3, sitting height was additionally measured as described in Section 3.1.3.3 (Sitting height and leg length) to obtain leg length to be used in the calculation of leg stiffness in Section 3.2.3 (Neuromuscular Response Testing) and to calculate age at peak height velocity (PHV) and maturational offset (Mirwald et al., 2002).

Table 3.1 Study 1 participant anthropometrics

Number of participants	64
Age (years)	15.2 ± 0.5
Weight (kg)	58.0 ± 7.9
Height (cm)	163.6 ± 5.5

Table 3.2 Studies 2 and 3 participant anthropometrics

Number of participants	36
Age (years)	15.03 ± 0.64
Weight (kg)	56.2 ± 6.5
Height (cm)	161.9 ± 5.3
Sitting Height (cm)	83.4 ± 3.8
Leg length (cm)	78.5 ± 4.0
Age at Peak Height Velocity (years)	12.9 ± 0.4
Maturational Offset (years)	2.3 ± 0.6

3.1.3.1 Body mass

Participants were measured for body mass using a combined stadiometer and scales (Seca, Hamburg, Germany). Participants were measured in a training top, shorts, and socks. Participants were asked to step on the scales, to stand straight and not looking at the floor, to maintain balance and hold completely still for two seconds. The scales automatically turned off after each measurement and were reset to zero before each participant stepped on to the scales. Body mass was assessed to the nearest 0.1 kg.

3.1.3.2 Stature

Participants were measured for stature using a combined stadiometer and scales (Seca, Hamburg, Germany). Participants were asked to place their heels, buttocks, upper back, and head against the stand, standing tall with feet together. Participants wore socks for the measurement. The researcher placed their hands on the mandible of the participant and moved their head into the Frankfort plane (Stewart et al., 2011). Maintaining light pressure on the mastoid process, the researcher moved the headboard onto the participant’s head, using downward pressure to compact any hair volume. Participants were then instructed to stand as still as possible. Stature was taken to the nearest 0.1 cm.

3.1.3.3 Sitting height and leg length

Participants were measured for sitting height using a portable stadiometer (Seca, Hamburg, Germany). Participants were asked to sit on the base on the stadiometer with their legs straight on the floor, placing their buttocks and shoulders against the stand, sitting tall and without posterior rotation of the pelvis or arching of the back. The researcher placed their hands on the mandible of the participant and moved their head into the Frankfort plane (Stewart et al., 2011). Maintaining light pressure on the mastoid process, the researcher moved the headboard onto the participant’s head, using downward pressure to compact any hair volume. Participants were then instructed to sit as still as possible. Sitting height was taken to the nearest 0.1 cm. Leg length was calculated by subtracting sitting height from stature.

3.1.4 Testing locations and conditions

Sprint testing (Study 1) occurred outdoors at each team's training facility and was performed on 3G or 4G astroturf. Sprint testing was conducted with different teams during the regular soccer season at times ranging from mid-autumn to early spring (October to April). Testing was conducted outdoors in the evening at the beginning of each team's usual training session (between 5:30pm and 8:30pm) where the following range of weather conditions were reported: weather conditions were cloudy or clear but without precipitation; temperature ranged from 4 – 11˚C, with an average humidity of 84% (±11%), and wind speed range of 1.8 – 4.9 $m \cdot s^{-1}$.

Matches (Studies 2 and 3) were played at a variety of venues in England on regulation size pitches. All matches were played outdoors on grass or 3G astroturf. Testing took place in two periods of the normal competitive season from late September to November and from February to May. Weather conditions for each match are included in Appendix 3.1 (Time and Date AS, n.d.). All matches were played on Saturdays in daylight in the morning or afternoon. Matches in the study included regularly-scheduled league matches, cup matches, and friendly matches that were played against other RTCs during the 2017-2018 and 2018-2019 seasons. A summary of match details including match outcomes for each team is provided in Table 3.3.

Table 3.3 Match details for Study 2

	Team A	Team B	Total
# of matches	9	11	20
Played on Grass	9	9	18
Played on 3G	0	2	2
League	3	5	8
Cup	0	3	3
Friendly	6	3	9
Win	6	6	12
Loss	2	3	5
Draw	1	2	3
Morning Start (9:30-11:59)	9	9	18
Afternoon Start (12:00 – 16:00)	0	2	2
# of days between matches (range), 2017-2018, Feb - May	n/a	24.5 (14-35)	
# of days between matches (range), 2018-2019 1st period, Sep - Nov	10.5 (7-21)	42 (42)	
# of days between matches (range), 2018-2019 2nd period, Feb - May	14 (7-28)	15.4 (7-28)	

3.1.5 Global Positioning System (GPS) validity and reliability

A complete evaluation of the validity and reliability of the system was outside the scope of this thesis. However, there is a large body of work regarding the validity and reliability of GPS system for use in team sports to measure match loads including distance, speed, acceleration, and deceleration. Though previous research has concluded that 1 Hz and 5 Hz GPS systems are valid and reliable (Aughey, 2011), higher sampling frequency has been associated with greater validity of movement demand measures (Johnston et al., 2012; Nagahara et al., 2017; Petersen et al., 2009).

With the rapid development of GPS technology and increase in sampling frequency, validity and reliability of newer 10 Hz and 15 Hz systems have also been assessed (Buchheit et al., 2014; Johnston et al., 2014; Varley et al., 2012). A study comparing measures of straight-line running from 10 Hz GPS with a tripod-mounted laser demonstrated good interunit reliability was good for instantaneous velocity, accelerations, and decelerations ($p < 0.90$, CV = 1.9 – 6%) (Varley et al., 2012). Additionally, good validity was demonstrated in accelerations as measured from a range of starting velocities ($p<0.90$, CV: 3.6-5.9%), and moderate validity in decelerations ($p<0.90$, CV = 11%) (Varley et al., 2012). Buchheit et al (2014) examined the reliability of fifty 15 Hz GPS units attached to a single sled towed by a runner completing a standardised running routine on two consecutive days. Comparable measures were observed between days in total distance (<1% difference), total distance at speeds >4 $m \cdot s^{-1}$ (<3% difference), and number of high accelerations >3 and >4 $m \cdot s^{-2}$ (<3% difference) demonstrating good intersession reliability. Interunit reliability was good for total distance (CV: 2-6%), but good to poor and poor for counts of decelerations and accelerations, respectively (CV: 1-56%) (Buchheit et al., 2014), which is not in agreement with previous research, although this could be a reflection of the different systems used.

Johnston et al (2014) used two 10 Hz GPS units and two 15 Hz GPS units to assess the validity and reliability of GPS for match loads in a team sports circuit of known distance (1,320 m), additionally comparing peak speeds measured via GPS with peak speed measured via timing gates over a 10 m portion of a sprint in the circuit. The study found no significant differences in distance measures from the criterion measure of distance and good interunit reliability for both sampling rates types (typical error of measurement < 1.9%), and moderate to good correlation of peak speeds between GPS and timing gates (r = 0.64 – 0.91) with 10 Hz units demonstrating greater validity than 15 Hz units (Johnston et al., 2014). While 10 Hz units have demonstrated greater validity and reliability, 15 Hz units show improved measures compared with 1 Hz and 5 Hz units (Johnston et al., 2014), and have generally shown good validity and reliability in measuring movement variables.

To date, one study has evaluated the reliability and validity of the 15 Hz GPSports HPU system used in the current study (Tessaro & Williams, 2018). Tessaro and Williams (2018) evaluated the GPS system by mounting two GPS units on a calibrated trundle wheel, which was used to measure four running courses of different distances and at varying speeds, including changes of direction. The study found strong inter-unit reliability (ICC > 0.99) in comparing the two mounted GPS units. Although GPS overestimated distances compared to the wheel measure, the effect sizes for wheel measure v GPS for all four courses were small (Cohen's $d < 0.43$) with small bias values (< 2%), showing good validity. Intraclass correlation coefficients were also very large for all four courses (ICC > 0.95) demonstrating good reliability for the GPS system. Overall, GPS as a measure for distance and derived time-distance variables has been shown to have an acceptable level of validity and reliability to use in team sport settings.

3.2 Testing methods – sprint testing

Sprint testing took place during a team's normal training session. Testing sessions occurred on two occasions, one week apart at the same time of day on each week to mitigate the effects of circadian rhythm on exercise performance (Cappaert, 1999); one team had testing occur two weeks apart on the same day due to rescheduling. Three teams had two days of training each week with one or two days between and one team had two days of training each week on consecutive days. For all teams, the testing sessions occurred on the second training day of the week. Participants were not provided instructions to limit activity on days prior to sprint testing.

Participants wore a training top, shorts, and soccer boots. Participants took part in two sprint tests at the beginning of each training session. Participants were led through their individual team’s dynamic warm up for 10 minutes by a coach (sample warm up outlined in Table 3.4), followed by a 5-minute sprint-specific warm up led by the researcher that was conducted with all teams (Table 3.5). The testing session occurred before normal training activities. In the first testing session, each participant was placed in one of two randomised groups of equal numbers for testing, with each group completing one sprint test followed by the second test so participants completed both sprint tests in each testing session. In the event that groups had unequal numbers of participants where participants were running in pairs (Section 3.2.1.3 Maximal effort run), a third set of cones was set, and a trio of participants would complete the test in addition to the paired participants. Due to some participants being present for one testing session but not two, groups from the first testing session were reformed as near as possible in the second testing session and sprint test order was reversed for the second testing session.

Table 3.4 Sample warm up with examples from each team's individual warm up as led by the team coach prior to the sprint-specific warm up

Sample Team Warm Up – Coach Led
10 minutes
Half-lap jog
Straight line jogging, 4 x 15 m
Running open/close the gate, 2 x 15 m
Side shuffle and carioca, 2 x 15 m
Forwards and backwards jog, 2 x 15m
Plank and side plank, 1 rep each x 30 s
Nordics, 5 reps
Side lunges, 5 reps each direction
Squat to jump, 5 reps
Hop in place, 5 reps

Table 3.5 Sprint-specific warm up conducted with each team in preparation for sprint testing

Sprint-specific Warm Up – Researcher Led
5 minutes
A-line march, 2 x 15 m
A-line skip, 1 x 15 m
2 leg to 1 leg stick, 1 x 15 m
Alternate leg triple hop + land, 2 x 15m
Sprint ramp up – 75, 85, 100%, 3 x 15m

3.2.1. Global Positioning System (GPS) motion capture

GPS data was collected using a 15 Hz GPSports HPU system (Canberra, Australia). Prior to training, units were turned on outdoors and left stationary for five minutes to sync with satellite signals per the manufacturer's instructions. Participants were provided with a manufacturer-specific vest for the GPS unit that was worn over their training top during training sessions. Vests were provided to each participant for tightest fit to reduce movement artefact. Each vest contained a pocket for the GPS unit that held the unit between the participant's scapulae. When the GPS units had synced with satellite signals as confirmed by the flashing green light on each unit, the units were placed in the vest pocket in the correct orientation per manufacturer's specifications and visually checked to confirm that the participant's heart rate monitor was synced to their unit via the red light on the GPS unit. Participants were assigned the same GPS units at both testing sessions to minimise the potential effect of interunit variability (Scott et al., 2016). Participants were familiarised with the GPS system during warm up prior to testing sessions.

3.2.2 Sprint test – 30.5 m

A linear sprint speed test was undertaken to assess maximal sprint speed (MSS) using a sprint distance of 20 m that aligns with reported average sprint distances of 17 (±1) m for U16 female soccer players during matches (Vescovi, 2014). A 10 m deceleration zone to a complete stop was included to measure the distance accuracy of GPS at high speeds. A sprint course was set using SmartSpeed PRO system timing gates (TG; Fusion Sport, Queensland, Australia) placed at 0 m, 10 m, 20 m, and 30 m as in Figure 3.1. A 100 m tape measure (Group Silverline Ltd, Yeovil, United Kingdom) was used to measure a distance of 30 m. Markers were placed at 0 m, 10 m, 20 m, and 30 m. Two cones were placed 40 cm behind the

0 m markers, and a finish cone was placed 10 cm after the 30 m markers in the centre of the course. The starting cones were placed 40cm before the first set of timing gates (Timing gate 0 m) to ensure participants did not prematurely break the light beam. Similarly, the finish cone was placed 10 cm after the last set of timing gates (Timing gate 30 m) to ensure participants would fully pass through the gate. Timing gate light cells mounted on tripods were placed directly over the markers on the left of the sprint course at a height of approximately 65 cm. Tripods with a reflector for the light cell were placed directly over the markers on the right, 1 m from the light cell and at the same height. The timing gates were turned on and adjusted to correctly reflect the light beam. The SmartSpeed Pro system was set to a four-gate sprint test with 10 m between each timing gate and for the system to run automatically.

The participant stood in a split stance with their preferred lead foot directly over the starting line marked by two cones (Starting Cones) for three seconds. When the timing gate system was ready, the light cells all showed a green light and the participant could use the course when they were ready. After the light cells turned green and the participant had stood in place for three seconds, the participant ran as quickly as possible through the timing gates to reach what they felt was their maximum speed by the third set of timing gates (Timing gate 20m), marked with yellow cones. After reaching the third set of timing gates, the participant could begin to decelerate to come to a complete stop standing directly over the finish cone with both feet parallel on either side of the finish cone (Finish Cone), where they were instructed to stand for three seconds. The green light in each light cell would turn off when the participant had passed through the timing gate and a short beep noise could be heard indicating that timing had started for each gate. When the participant had completed the course by passing through the fourth timing gate at 30 m, the system reset by displaying flashing lights. The next participant could begin their sprint after the lights reset to green and they had stood still for three seconds. Coaches at the starting cones and finish cone reminded participants to stand still for three seconds at each location and gave verbal encouragement to participants during the test. Participants repeated the sprint three times, with approximately two minutes of rest between each sprint.

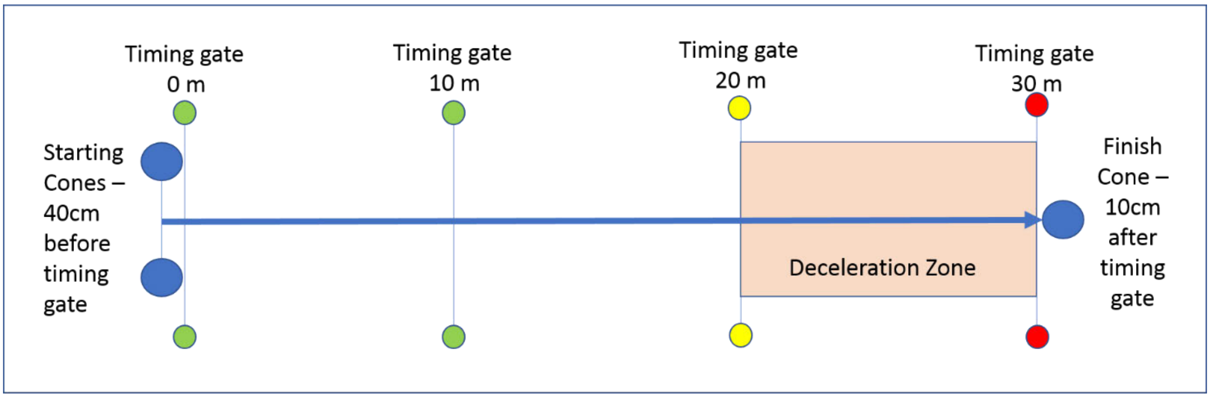


Figure 3.1 Diagram of 30.5 m sprint test

Figure 3.2 Photo of course setup for 30.5 m sprint test

3.2.3 Maximal effort run

A 100 m tape measure (Group Silverline Ltd, Yeovil, United Kingdom) was used to measure a distance of 92 m. Two cones were placed approximately 2 m apart at 0 m and 92 m as in Figure 3.3. The two 92m courses were set side by side for two participants to participate at the same time to provide a race-like situation. Participants stood over the starting cone (Starting Cone) for three seconds in a split stance start with their front foot just over the cone. Participants were instructed to increase their speed gradually and to reach what they felt was their maximum speed at some point during the course, and to then decelerate and come to a complete stop standing directly over the finish cone with both feet parallel to either side of the finish cone (Finish Cone), where they were instructed to stand for three seconds. Coaches at the starting cones and finish cones reminded participants to stand still for three seconds at each location and gave verbal encouragement to participants during the test. Participants repeated this run three times with approximately three minutes of rest between each sprint, including a slow recovery walk back to the starting cone.

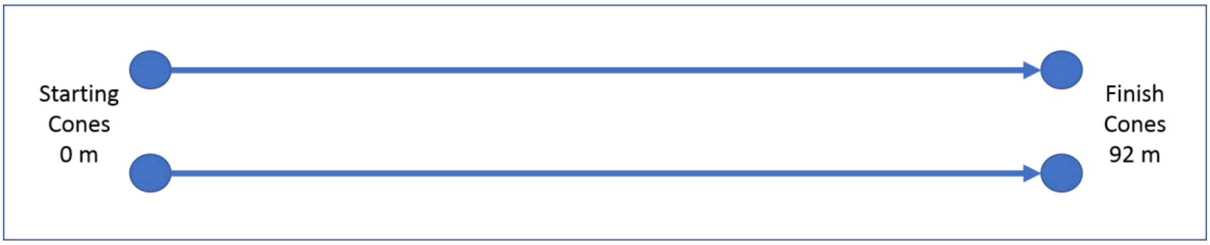


Figure 3.3 Diagram of the maximal effort run test

3.2.4 GPS and timing gate data processing

After each testing session, units were placed into the GPS system docking station for unit files to load onto the docking station memory. Files were then downloaded to a computer from the docking station using the TeamAMS software (R2016.7, GPSports, Canberra, Australia).

Speed was calculated from the change in distance divided by the change in time. For the 30.5 m sprint test, maximum sprint speed was used as derived from the manufacturer-provided TeamAMS software. This was calculated by the software using the GPS unit’s measurement of location to provide a change in distance over the known change in time (1/15 of a second) between location measurements. Individual runs were isolated in the software and the raw data downloaded as Excel spreadsheets for analysis.

The SmartSpeed timing gate system provided timings from 0 – 10 m, 10 – 20 m, and 20 – 30 m, which were downloaded to a laptop computer as CSV files from the Fusion Sport server and converted to Excel spreadsheets for analysis. From the provided timings for each sprint, speed for 0 – 10m and 0 – 20m and flying sprint speed for 10 – 20 m were calculated. For maximal effort runs, maximum sprint speed was used as derived from the GPS units. Individual runs were isolated in the software and the raw data downloaded as Excel spreadsheets for analysis.

3.3 Testing methods – matches

3.3.1 GPS in matches

As part of an FA Regional Talent Club, participants trained on Wednesday (Team A) or Thursday (Team B) evenings, had no RTC-scheduled activities on Friday evenings, and played all matches on Saturday mornings or afternoons. For the 24 hours prior to a match, participants were provided RTC-developed guides and were instructed by coaches and RTC support staff to use rest and recovery strategies, to avoid strenuous activity before a match, and to have an appropriate diet for pre-match preparation. Eleven participants reported having physical education classes on Fridays.

On match day, one hour prior to each match, participants who were fully taking part in the match and were deemed fit by team medical staff were provided with a manufacturer-specific vest for the GPS unit (Section 3.2.1.1 Global Positioning System (GPS) motion capture) that was worn under their match top during matches per FA rules. Vests were provided to each participant for tightest fit to reduce movement artefact. Each vest contained a pocket for the GPS unit that held the unit between the participant's scapulae. Participants were provided with Polar T34 heart rate monitors (Polar, Kempele, Finland) that automatically synced to their individual GPS units, worn against the skin around the chest at the level of the xyphoid process.

When the GPS units had synced with satellite signals as confirmed by the flashing green light on each unit, the units were placed in the vest pocket in the correct orientation per manufacturer's specifications and visually checked to confirm that the participant's heart rate monitor was synced to their unit via the red light on the GPS unit. All participants had previously worn the units and heart rate monitors on at least one prior occasion during training. Participants were provided with the same GPS unit at each match wherever possible to minimise the potential effect of interunit variability (Scott et al., 2016).

Participants took part in a 20-25 minute warm up led by team coaches (Table 3.6). Matches were fully refereed, consisting of two halves of 40 minutes each and a 10-minute half time rest period. Start and end times for each half were marked using a GPS-synced watch (Vivoactive 3, Garmin, Olathe, KS, USA). Some match halves were longer than 40 minutes due to stoppage time for injury as allocated by the referee. As participants were not active during injury periods and then given allocated time to offset these inactive periods, extra minutes were not considered as additional time. No matches had extra time periods.

Table 3.6 An outline of the pre-match warm up used by each team's coaches

Team A	**Team B**
20-25 minute pre-match warm up	
5 minutes – raise heart rate Running straight ahead, increasing intensity – 3 reps x 30 m Running open the gate – 2 reps x 30 m Running close the gate – 2 reps x 30 m Running circles partnered – 2 reps x 30 m Running contact partnered – 2 reps x 30 m Running quick forwards and back – 2 reps x 30 m **6 minutes – activate and mobilise** Plank – 2 reps x 20 s	**4 minutes – raise heart rate** Jogging – half pitch lap A-line walks – 1 rep x 10 m A-line skip – 1 rep x 10 m Linear jog with backpedal – 2 reps x 10 m Curved running with in's and out's – 2 reps x 10 m **6 minutes – activate and mobilise** Slow banded overhead squats – 10 reps Banded crab walks – 1 rep x 10m Banded monster walks – 1 rep x 10m

Side plank – 1 rep x 20 s each side Hamstring lowering – 3-5 reps Single leg jump and land – 1 rep x 15 m each leg Squat to toe raise – 3-5 reps x 2 Squat to jump – 3-5 reps x 2 **3 minutes - potentiate** Reactive agility – 2 reps x 30 s Running plant and cut – 2 reps x 15 m 70 – 80% max run – 2 reps x 15 m **5 – 10 minutes – soccer drills** Passing drill – 2 minutes Small side possession – 3-8 minutes	Leg swings – 10 each leg, each side Single leg Romanian deadlift – 5 reps Glute pull to reverse lunge – 1 rep x 10m Lateral lunge to kick – 1 rep x 10m Side shuffles – 1 rep x 10m Carioca – 1 rep x 10m **5 minutes - potentiate** Broad jump and walk back – 5 reps Single leg hop and stick – 3 reps each side Linear single leg rebound and stick – 3 reps each side Lateral hop and stick – 3 reps each side Double leg pogos – 2 reps x 10m Max intensity acceleration – 4 x 10m **5 – 10 minutes – soccer drills** Passing drill – 2 minutes Small side possession – 3-8 minutes

3.3.2 Neuromuscular response testing

Neuromuscular response tests (NRMT) were conducted approximately 45 minutes prior to matches and before the team warm up, and post-match after a brief cool down and return to the player changing area, approximately 10 minutes after matches were concluded. Participants took part in the pre-match NRMT if they were deemed fit by the match day medical staff and were fully participating in the match. If a participant was injured in the course of the match, they were excluded from post-match testing.

Three tests were conducted both pre- and post-match using SmartJump mobile contact mats (Fusion Sport, Queensland, Australia) in the following order: a maximal hop test, a submaximal hop test, and a countermovement jump (CMJ) test. A rest period of at least one minute was observed between each test. The maximal and submaximal hop tests were conducted as proposed in previous work assessing NMR in youth athletes (Lloyd et al., 2009) and the countermovement jump test was modified from the procedures described by Mohr and Krustrup (2013) to use three CMJs with a brief rest period between jump efforts instead of 5 CMJs (Mohr & Krustrup, 2013).

All NMRTs were conducted with SmartJump contact mats powered by a SmartSpeed Pro timing light wirelessly connected to a SmartSpeed PRO system Hub unit. All tests were initiated and controlled by the researcher through the SmartSpeed app for Apple iOS which stored the test data. Participants were given verbal instructions prior to each test and then asked to step on the contact mat at the appropriate time for each test. Data was uploaded to the Fusion Sport server and was subsequently downloaded to a laptop computer in CSV files and converted to an Excel worksheet for analysis.

Participants were familiarised with the hop procedures and techniques prior to match testing during previous training sessions. Team A was familiarised with the hop and CMJ techniques and procedures at a training session in the week prior to the first match. Team B was familiarised with the hop technique and the CMJ in the course of their regular strength and conditioning training. Both teams were re-familiarised with the hop and jump techniques and procedures on the day of the first match when testing occurred, immediately prior to testing. Participants were reminded of the techniques and provided the opportunity to conduct three or four submaximal hops prior to testing and one submaximal CMJ. At subsequent matches, participants did not require re-familiarisation. At each match they were provided with the same instructions and encouragement by the researcher to promote adherence to correct procedure.

The maximal hop test using contact mats provides data used to calculate reactive strength index (RSI), a measure of the stretch-shortening cycle and an indicator of neuromuscular performance (Lloyd et al., 2011). The test has been shown to be reliable in youth populations (average measures ICC = 0.90, CV < 15%) (Lloyd et al., 2009). Post-hoc analysis was conducted with a small subset of the cohort from the current study using rested state, pre-match maximal hop test results for four consecutive weeks with the same 8 participants. Intraclass correlation coefficient for absolute agreement was 0.68 with a CV of 23%, demonstrating moderate reliability but high variation in contrast to previous research using a maximal hop test for RSI.

The submaximal hop test using contact mats provides a measure of leg stiffness, a method used to assess neuromuscular response to fatigue (Padua et al., 2006). The test has been previously validated by comparing leg stiffness measures quantified using mobile contact mats to criterion measures from force plate data (r = 0.94, p<0.001) (Dalleau et al., 2004). In youths, validity tests show a strong positive correlation between contact mat- and force plate-derived measures of leg stiffness at 2.0 Hz hopping frequency (r = 0.95) and an acceptable typical error of estimate (TEE = 6.5%) (Lloyd et al., 2009). More recently, the test was also shown to be reliable in female adolescent soccer players (CV < 10%) (De Ste Croix et al., 2016). Post-hoc analysis was conducted for the submaximal hop with a subset of 8 participants in the current study using pre-match submaximal hop test results over four consecutive matches. Relative stiffness measures were found to have good reliability (ICC = 0.90) with an average CV of 11%.

Finally, the countermovement jump test provides a measure of jump height which has been used in monitoring neuromuscular response to match-play in team sports (Claudino et al., 2017). Though the CMJ measured on a SmartJump mobile contact mat was shown to overestimate jump height compared to criterion force plate data ($p < 0.001$), the magnitude of difference between contact mat and force plate methods was not significant (mean difference + 1.37 cm, $p = 0.904$) (Reeve & Tyler, 2013). Further studies show strong within-day reliability (ICC > 0.90, CV < 3%) in youths (Rodríguez-Rosell et al., 2017) and similarly strong between-session reliability using a contact mat for mean CMJ jump height over three sessions each conducted one week apart (ICC > 0.90, CV ≤ 6%) (Moir et al., 2008), similar to week to week testing that took place during the current study. Post-hoc analysis with a subset of 8 participants from the current study using pre-match CMJ test results over four consecutive matches showed similarly strong reliability (ICC = 0.94) and low CV (5%). Overall, these tests are valid and reliable in measuring and detecting changes in neuromuscular response.

3.3.2.1 Maximal hop test

The maximal hop test consisted of five consecutive bilateral hops. Participants were instructed to keep their hands on their hips at all times during the test; to jump with straight legs, (i.e. not to flex their knees when in the air or in contact with the ground); to keep the head and torso upright, with eyes looking forward; to spend as much time in the air as possible; to minimise time in contact with the mat; and to hop in one place in the centre of the contact mat without excessive movement around the mat. Participants were asked to reperform the test if they were unable to maintain balance, moved excessively around the mat, removed their hands from their hips, or did not jump with straight legs. Participants stepped onto the contact mat prior to the start of the test. When the SmartSpeed light turned green, participants could begin the test when they were ready. The SmartSpeed system counted five hops and the lights turned off when the participant had completed the test.

The first hop was a countermovement jump and was discounted for the purposes of this test and the remaining four hops were used for analysis. Data from the maximal hop test include flight time and contact time, from which jump height (JH) and reactive strength index (RSI) is calculated. Flight time (Ft) was defined as the time in seconds between the participant leaving and returning to the contact mat during a jump. Contact time (Ct) was defined as the time in seconds between the participant returning to the contact mat after the jump and leaving the contact mat for the subsequent jump. JH in metres was calculated using the formula:

$$JH = \frac{(g \ \times Ft^2)}{8}$$

where g is the acceleration due to gravity ($9.81 \text{ m}\cdot\text{s}^{-2}$) and Ft is flight time in seconds (Bosco et al., 1983). RSI was calculated for each participant, where JH is divided by Ct (Flanagan & Comyns, 2008) using the JH and Ct from the four hops which are then averaged (Oliver et al., 2015).

3.3.2.2 Submaximal hop test

The submaximal hop test consisted of 20 consecutive bilateral hops in 10 seconds, timed to a quartz metronome (Seiko, Tokyo, Japan) at a frequency of 2.0 Hz. Participants were instructed to keep their hands on their hips at all times during the test; to jump with straight legs, (i.e. not to flex their knees when in the air or in contact with the ground); to keep the head and torso upright, with eyes looking forward; to minimise time in contact with the mat; to hop in one place in the centre of the contact mat without excessive movement around the mat; and to hop in time with the metronome. Participants were asked to reperform the test if they were unable to maintain balance, moved excessively around the mat, removed their hands from their hips, or did not jump with straight legs. Participants stepped onto the contact mat prior to the start of the test. The metronome was turned on and participants were given to the count of three for the test to start. Participants were encouraged to match the feedback sound from the contact mat system to the metronome to attain proper hopping frequency. The SmartSpeed system counted 10 seconds and the feedback sound ceased when the test was completed. Data from the submaximal hop test include individual hop Ft and Ct, from which absolute and relative leg stiffness is calculated. As participants were not hopping at the appropriate frequency for the initial hops, the first five hops were discounted for the purposes of this test. Only 10 consecutive hops where hop frequency was subjectively judged to be closest to 2.0 Hz were used for analysis. Leg stiffness in kN·m^{-1} was calculated using the formula:

$$Leg\ stiffness = \frac{M \times \pi\,(Ft + Ct)}{Ct^2(\frac{Ft + Ct}{\pi} - \frac{Ct}{4})}$$

where M is the total body mass of the participant (Dalleau et al., 2004). Relative leg stiffness (dimensionless) is calculated by multiplying the leg stiffness by a factor of M and leg length

(m) (McMahon & Cheng, 1990). The average relative leg stiffness was calculated from the relative leg stiffness of the individual 10 consecutive hops.

3.3.2.3 Countermovement jump (CMJ) test

The countermovement jump (CMJ) test consisted of three bilateral CMJs with a brief rest period between each jump. Participants were instructed to keep their hands on their hips at all times during the test. Participants were asked to conduct a countermovement to a self-selected depth and to not pause at the lowest depth and to then jump as high as possible and land on both legs equally (Cormack et al., 2008; Young et al., 1995). Participants were instructed to reset to the start position of standing upright with hands on hips between each jump. Participants were asked to reperform the test if they did not maintain their balance in landing or removed their hands from their hips. Participants were verbally encouraged to provide maximal effort during the test. Participants stepped onto the contact mat to start the test and could begin the test when they were ready. The SmartSpeed system counted three jumps and the system lights turned off when the participant had completed the test. Data from the countermovement jump test include Ft which was used to calculate jump height as described in Section 3.3.2.1 (Maximal hop test). The average of the three jumps was used for analysis, due to the sensitivity of average CMJ height to detect changes in neuromuscular response compared with highest CMJ height (Claudino et al., 2017).

3.3.3 GPS data processing and match variables

After matches, units were placed into the GPS system docking station for unit files to load onto the docking station memory. Files were then downloaded to a computer from the docking station using the TeamAMS software.

In Study 2, GPS files were cut to include only a participant's time on the pitch during a match, which was recorded via a GPS-synced watch to the nearest minute. Data used from the TeamAMS software are included in the variables listed in Table 3.7.

Table 3.7 Study 2 match variables

Variable	Unit of measurement
Total distance (TOTAL)	m
Time played	min
Work rate (WR)	$m\cdot min^{-1}$
Sprint distance ($\geq 5.6\ m\cdot s^{-1}$) (SPR)	m
High-speed running distance (≥ 4.3, $< 5.6\ m\cdot s^{-1}$) (HSR)	m
Low-speed running ($< 4.3\ m\cdot s^{-1}$) (LOW)	m
Average speed (AVG)	$m\cdot s^{-1}$
High-speed activity (HSA) ($\geq 4.3\ m\cdot s^{-1}$)	m
# of sprint-speed efforts (defined by sprints $\geq 5.6\ m\cdot s^{-1}$ for ≥ 1 s duration) (SSE)	
# of high-intensity accelerations (defined by acceleration $> 2.0\ m\cdot s^{-2}$ for ≥ 1 s duration) (HIA)	
# of repeat HIA (occurring < 30 s) (REPEAT)	
# of accelerations ($> 1.0\ m\cdot s^{-2}$) (ACCEL)	
# of decelerations ($< -1.0\ m\cdot s^{-2}$) (DECEL)	
Average heart rate (average HR)	beats per minute

Variables provided by the TeamAMS software and calculated for the purpose of analysis as listed in Table 3.7 are determined as follows:

- *Total distance (TOTAL)* – the change is displacement of a participant measured by the GPS during the time played; total distance is the sum of each period of time played for a participant (e.g. the sum of total distance in the first and second halves)
- *Work rate (WR)* – the distance divided by the time played in a given time period
- *Sprint-speed running distance (SPR)* – distance derived by the TeamAMS software, recorded when a participant was in motion above the sprint speed threshold of $5.6\ \text{m}\cdot\text{s}^{-1}$
- *High-speed running distance (HSR)* - distance derived by the TeamAMS software, recorded when a participant was in motion within the high-speed running zone of $\geq 4.3, <5.6\ \text{m}\cdot\text{s}^{-1}$
- *Low-speed running distance (LOW)* – distance derived by the TeamAMS software, recorded when a participant was in motion below the high-speed running threshold of $4.3\ \text{m}\cdot\text{s}^{-1}$
- *Average speed (AVG)* – speed derived by the TeamAMS software as an average of recorded speeds in a given time period during match-play
- *High-speed activity (HSA)* – distance derived by the TeamAMS software, referring to combined variables of HSR and SPR where motion is $\geq 4.3\ \text{m}\cdot\text{s}^{-1}$
- *Number of sprint-speed efforts (SSE)* – a count of the number of running efforts where a participant's speed is $\geq 5.6\ \text{m}\cdot\text{s}^{-1}$ for a duration of >1 s, counted by the TeamAMS software
- *Number of high-intensity accelerations (HIA)* – a count of maximal running efforts where acceleration exceeds $2.0\ \text{m}\cdot\text{s}^{-2}$ for a duration of >1 s, counted by the TeamAMS software

- *Number of repeat HIA (REPEAT)* – using the definition of HIA defined by acceleration >2.0 $m \cdot s^{-2}$ for >1 s duration, a repeat HIA is the subsequent effort that occurs less than 30 s after the first, as counted by the TeamAMS software
- *Number of accelerations (ACCEL, >1.0 $m \cdot s^{-2}$) and decelerations (DECEL, <-1.0 $m \cdot s^{-2}$)* – per the manufacturer-provided guide (GPSports, n.d.), accelerations and decelerations are calculated from 5 GPS data points to provide a line of best fit; average change in speed is reported from the gradient of the line and three acceleration or deceleration measures are calculated per second
- *Average heart rate (HR)* – the total of the heart rate measures (recorded at a frequency of 5 Hz) divided by the time played, as calculated by the TeamAMS software

CHAPTER 4

Defining Sprint-Speed Thresholds for Adolescent Female Soccer Players

4.1 Introduction

To evaluate match load, global positioning systems (GPS) are frequently used in team sports due to ease of use through automation and the ability of GPS to accurately track player movement on a pitch (Scott et al., 2016). To quantify match load and to allow for comparisons between players and teams, speed thresholds are used to sort movement tracked by GPS into speed zones. In soccer, particular emphasis is placed on quantifying high-speed movement due to its importance in match performance and for tracking of fatigue onset during match-play (Dwyer & Gabbett, 2012; Mohr et al., 2003). Different thresholds have been recommended (Bradley & Vescovi, 2015; Datson et al., 2017; Dwyer & Gabbett, 2012; Park et al., 2018) and used in adolescent female soccer (Ramos et al., 2019; Vescovi, 2014), however, none are specific to adolescent female soccer.

Previous studies of match load in adolescent female soccer for U15, U16, and U17 teams (Ramos et al., 2019; Vescovi, 2014) analysed match-play using the same sprint-speed threshold which is based on maximal sprint speed (MSS) testing in adult female players and recommended for female players ≥16 years of age (Bradley & Vescovi, 2015). In one study comparing U17 player match load to U20 and Senior players at international level, U17 players had lower total sprint distance compared to U20 and Senior players (Ramos et al., 2019). In another study comparing U15, U16, and U17 player match loads, U15 players had significantly less total sprint distance and lower number of sprints than U16 and U17 players (Vescovi, 2014). These findings suggest the sprint-speed threshold derived from adult data may be too high for adolescent players, particularly younger age groups. However, the study comparing match loads of adolescent age groups found no significant difference in measured maximal speed or average sprint distance between the U15, U16, and U17 age groups during match-play despite U15 players sprinting less (Vescovi, 2014), which may show that U15 players utilise their sprint ability less within match-play. As literature of sprint-speed movement in adolescent female match-play is limited to these studies, further understanding of adolescent sprint-speed movement within match-play is needed. To appropriately analyse adolescent sprint-speed movement, investigation of sprint speed abilities of adolescent players younger than 16 years of age in relation to the previously utilised and recommended speed threshold is needed prior to analysis of match load of U16 players.

In determining an appropriate sprint-speed threshold for match-play analysis, the use of a sprint-speed threshold based on MSS has ecological validity for motion analysis (Datson, 2016; Mendez-Villanueva et al., 2011). To do this, recent commentary recommends the use of longer sprint test distances of 30-40 m and using 80-85% of the reported MSS as a sprint threshold (Bradley & Vescovi, 2015). In particular, tested sprint speed using 30-40m distances is needed due to longer sprint distances differentiating sprint speed ability between age groups (J. D. Vescovi et al., 2011). In comparing sprint speed ability between age groups, increases with chronological age have been reported until a plateau around 15 – 16 years (Vescovi et al., 2011), which aligns with a plateau in maturation in females (Catley & Tomkinson, 2013; Malina et al., 2004; Malina et al., 2010). Small increases in sprint speed ability are also observed beyond this plateau with increasing age (Mujika et al., 2009; Vescovi et al., 2011). Further, differences in sprint speed are noted between adolescent age groups of similar levels and between performance standards (Datson, 2016; Hoare & Warr, 2000). Due to this variety of sprint speed ability, especially in ages groups younger than 16 years of age, one aim of this study is to investigate the sprint speed ability of U16 female soccer players.

The recommendation for using 80-85% of MSS tested over 30-40 m is also based in part on player use of MSS in match-play, with one study of adolescent male soccer players finding players reached a high percentage of their individual MSS (84-91%) during matches (Mendez-Villanueva et al., 2011). Sprints in match-play are usually of short duration due to the nature of the game, which is why players infrequently utilise their maximal sprint speed ability (Mendez-Villanueva et al., 2011). Average sprint distances of 16 m in match-play were reported in female adult soccer at state competition in Brazil (Nakamura et al., 2017) and 15 m in professional-level soccer in the US (Vescovi, 2012a). These short sprint distances are similar to those reported for U15 and U16 female age groups, with average sprint distances of 16 and 17 m respectively (range 13-19 m) (Vescovi, 2014). From this, it could be inferred that using MSS tested over shorter, soccer-specific distances of 20 m to determine sprinting thresholds could be more specific to analysing match-play and allow for performance analysis across larger cohorts.

Previous studies of MSS in adult and adolescent female soccer players utilised timing gates to measure sprint speed (Datson, 2016; Emmonds et al., 2020; Hoare & Warr, 2000; Vescovi et al., 2011). Timing gates were also used to measure sprint speed in adult and professional-level players which informed the recommended sprint-speed threshold used to analyse adolescent player match load (Vescovi, 2012b). While the use of a sprint-speed threshold based on MSS has ecological validity in evaluating match load (Datson, 2016; Mendez-Villanueva et al., 2011), match load is not quantified using timing gates. Early studies of validity and reliability of GPS (1 Hz) used timing gates as criterion measures (MacLeod et al., 2009; Townshend et al., 2008), effectively comparing average GPS speed measures and average timing gate measures over known distances (Scott et al., 2016). With the advancement of GPS technology including measuring rates of 10 or 15 Hz, GPS measures of speed are possible over more discrete times allowing for measures of peak speed (Scott et al., 2016). In determining MSS for sprint-speed threshold, peak speed measured by GPS may provide a more ecologically valid measure of MSS to be used with GPS to quantify match load.

To this end, this study evaluated the sprint speed abilities of adolescent female soccer players (U16) via sprint tests using GPS and timing gates (TG). In doing so, the study compared the use of a match-play-specific sprint distance to a longer flying MSS test distance to evaluate MSS, compared average sprint speed from timing gates with GPS-derived peak speed, and investigated the appropriateness of a previously recommended sprint-speed threshold for GPS analysis of U16 female player match load.

4.2 Methods

4.2.1 Experimental approach to the problem

This study aimed to investigate the appropriateness of applying an adult female sprinting threshold for GPS motion analysis to an U16 female soccer player population, in fulfilment of research objective 1 of this thesis. Sixty-four adolescent female soccer players from three Football Association (FA) Regional Talent Clubs (RTCs) and one FA Charter Standard Count League team were assessed for MSS using two sprint tests of different distances using GPS. Timing gates on the shorter of the two tests were used simultaneously to provide comparison to previously reported data and to assess the reliability of the GPS system used in the study to measure sprint speed.

4.2.2 Participants

Sixty-four players from four U16s teams participated in the study (Mean ±SD age: 15.2 ± 0.5 years; stature: 163.6 ± 5.5cm; mass: 58.0 ± 7.9kg). Testing occurred on two occasions during each team's normal training session one week apart on the same day of the week and at the same time of day. One team had to conduct the second session two weeks from the first, also on the same day of the week and time to mitigate the effects of circadian rhythm on exercise performance (Cappaert, 1999). Fifty participants completed 3 trials of the 30.5 m sprint test using timing gates at one testing session; 41 of these participants had complete data for the 30.5 m sprint test from the timing gates and GPS simultaneously. Fourteen participants attended two testing sessions and had complete data for 3 trials of the 30.5 m sprint test each session. Twenty-eight participants attended two testing sessions and had complete data for 3 trials of the maximal effort run test each session. Participants and their parent or guardian gave written consent for the participant's anonymised data to be used in this study.

4.2.3 Procedures

Data for the study was collected using 15 Hz GPS units (GPSports HPU, Canberra, Australia) and SmartSpeed PRO system timing gates (Fusion Sport, Queensland, Australia). The validity of this GPS system is discussed in the General Methods (Chapter 3, section 3.1.5 Global Positioning System (GPS) validity and reliability). GPS was used to compare MSS in both sprint tests. Prior to each training session, participants were provided with a vest from the GPS manufacturer to wear over their training tops. Vests were sized for tightest fit to reduce movement artefact. The vest included a pocket that held the GPS unit between the participant's scapulae. All participants participated in a coach-led team-specific warm up for 10 minutes and a 5-minute standardised sprint-specific warm up led by the researcher

(Chapter 3, Tables 3.4 and 3.5). Each testing session consisted of two sprint tests, a 30.5 m sprint test and a 92-m maximal effort run (MER). On the day of testing, each team was divided into two random groups of equal numbers; each group completed one sprint test followed by the second sprint test, so participants completed both tests during a testing session. Due to some participants not being present for both testing sessions, groups from the first testing session were reformed as close as possible the following week and participants completed the tests in reverse order. In each testing session, participants completed three trials of each test, with two minutes of rest between each 30.5 m sprint trial and three minutes of rest between each MER.

The 30.5 m sprint test consisted of a linear sprint test with a 10 m acceleration split, a 10 m flying split, and a 10 m deceleration zone. The use of a 20 m sprint test was to assess participant speed over the reported average sprint distances for U16 players (Vescovi, 2014). Each participant started in a split stance position over the start cone 40 cm behind the first timing gate and stood still for three seconds. After three seconds, the participant then sprinted as fast as possible through the timing gate at the 20 m markers. After the 20 m markers, the participant had a 10 m deceleration zone to come to a complete stop at the finish cone 10 cm after the final timing gate at 30 m with feet parallel to either side of the cone. Coaches verbally encouraged participants during the test and reminded participants to come to a complete stop at the end of the sprint. Participants completed three trials of the sprint with 2 minutes of rest between each trial. MSS was taken from the raw GPS data. Timing gate sprint times from the 1st m split, 2nd 10 m flying split, and the cumulative 0-20 m sprint were recorded. Complete details of the test protocols can be found in the General Methods (Chapter 3, section 3.2.2 Sprint test – 30.5 m).

For the 92 m MER, participants ran in pairs to create a competitive atmosphere similar to match-play; if there was an odd number of participants, a third course was set and one group ran in a trio. Two pairs of cones were placed 92 m apart in a straight line. Participants stood still over the start cone for three seconds. After three seconds, the participants began to run as instructed, gradually increasing their speed, reaching their maximum speed at some point during the course before coming to a complete stop over the finish cone and standing still for three seconds. Coaches verbally encouraged participants during the test and reminded participants to come to a complete stop over the finish cone. Participants completed three trials of the run with 3 minutes of rest between each trial. Maximal speed during the test was taken from the raw GPS data. Complete details of the test protocols can be found in the General Methods (Chapter 3, section 3.2.3 Maximal effort run).

GPS data was uploaded to the manufacturer-provided software (TeamAMS R1 2016.7) for analysis. Participants' individual sprints were isolated using the software and the data downloaded as CSV files and converted to Excel for analysis using Excel (Microsoft, Redmond, WA). For each participant, the highest GPS speed during the sprint was noted for each trial. Timing gate data was uploaded to the SmartSpeed Fusion cloud-based website and downloaded as CSV files for analysis using Excel. Timing gate speed was calculated using split distance and timing gate sprint time recordings for 1st 10 m split, 2nd 10 m flying split, and 0-20 m sprint. Speed from the flying 10m (TGmax) was used for comparison to GPS speed (GPSmax) for the 30.5 m sprint test.

For the 30.5 m sprint test, a 10 m deceleration zone was included in the procedure but not in the data analysis. During testing it was noted that participants demonstrated varied deceleration skills. For example, some participants were unable to stop directly over the finish cone where others were able to decelerate quickly after passing the 20 m timing gate. However, the deceleration zone was included in the testing for ecological validity to relate to short sprint distances, similar to sprints in match-play with short duration sprint effort followed by a deceleration movement. However, deceleration values were not considered as part of the research question for this work and were therefore not included in the data analysis for this study.

4.2.4 Statistical analysis

Statistical analysis was conducted using Excel (Microsoft, Redmond, WA) and SPSS (Version 24, SPSS Inc., Chicago, IL). Data are presented as mean ± standard deviation (SD). Data were analysed for normal distribution using the Shapiro-Wilk test.

Fifty participants (n = 50) completed 3 trials of the 30.5 m sprint test. The highest speed for the 1st 10 m split, flying 10 m split, and 0-20 m sprint speeds are reported. Forty-one (n = 41) participants completed 2 or 3 trials of the 30.5 m sprint test with data available from both timing gates and GPS for each trial. To test the use of GPS to measure MSS compared with timing gates, 116 sets of TGmax and GPSmax speeds from the same trial of the 30.5 m sprint test were used. Pearson's correlation coefficient was calculated to compare GPS and timing gate speed. A paired t-test was used to assess the difference between the means of results from the two testing methods.

Fourteen participants (n = 14) completed three trials of the 30.5 m sprint test on two testing sessions for a total of 6 trials. The GPS data were used to test the reliability of the 30.5 m sprint test. Twenty-eight participants (n = 28) completed three trials of the MER test on two testing sessions for a total of 6 trials. These GPS data were used to test the reliability of the MER test. Within-session reliability was assessed using intraclass correlation coefficients (ICC) in two-way mixed-effects model for absolute agreement. The between-session mean of three trials (MEAN) and the best trial (BEST) were also assessed using ICCs. Paired t-tests assessed the difference in the means for MEAN and BEST and Cohen's *d* was calculated for effect size. Coefficients of variation as percentages were calculated to show intra-participant and between-session variability.

Sixty-four participants (n = 64) completed ≥2 trials of both the 30.5 m sprint test and the MER test. To compare the speeds from the 30.5 m sprint test and the MER test, the best trial and the mean of 2 or 3 trials from each test for each participant was used from the GPS data. Intraclass correlation coefficient (ICC) was used to assess the agreement between the tests of different distances using a two-way mixed-effects model for consistency. A paired t-test was used to assess the difference between the means of the two sprint tests.

Magnitudes of correlation for Pearson's were interpreted as very small (0.0-0.1), small (0.1-0.3), moderate (0.3-0.5), large (0.5-0.7), very large (0.7-0.9), and nearly perfect (0.9-1) (W.G. Hopkins, 2002). Intraclass correlation coefficients were rated as poor (<0.5), moderate (0.5-0.75), good (0.75-0.9) and excellent (>0.9) (Koo & Li, 2016). Effect size (ES) was considered small, moderate, large, very large, and extremely large with values greater than 0.1, 0.3, 0.5, 0.7, and 0.9, respectively (William G Hopkins et al., 2009). Coefficient of variation (CV) as a percentage was calculated as CV = (SD/mean)*100 and were rated as good (<5%), moderate (5-10%) or poor (>10%) (Duthie, 2003). Statistical significance was accepted at $p < 0.05$.

4.3 Results

Speeds calculated from timing gates times for the 1st 10 m split, flying 10 m split, and 0-20 m sprint are displayed in Table 4.1. The comparison of MSS measured concurrently from the 10 m flying sprint via timing gates and via the GPS for the 30.5 m sprint test is displayed in Table 4.2. Correlation between the methods of measurement was positive and large ($r = 0.67$, $p < 0.001$). A significant difference was found between the two measures of TGmax and GPSmax ($p < 0.001$) with a mean difference of -0.14 (95% CI: -0.20 – (-0.08))

Table 4.1 Calculated speed for each timing gate split and the 0-20 m sprint (mean ± SD)

n = 50 participants	1st 10 m split	Flying 10 m split	0-20 m sprint
Speed ($m \cdot s^{-1}$)	5.26 ± 0.25	6.96 ± 0.35	5.95 ± 0.27

Table 4.2 Comparison of GPS to timing gates using MSS measured simultaneously by each device (mean ± SD)

n = 116 trials	TGmax	GPSmax	Mean Δ	Pearson's r (p-value)
Speed ($m \cdot s^{-1}$)	6.76±0.37	6.90±0.43*	-0.14	0.67 (<0.001)

TGmax = MSS calculated from the flying 10 m split; GPSmax = MSS recorded via GPS; Mean Δ = mean difference, TGmax-GPSmax; *TGmax and GPSmax are significantly different ($p < 0.001$)

The within-session reliability results of the 30.5 m sprint test and the MER test are presented in Table 4.3. For the 30.5 m sprint test, ICCs for Session 1 and All trials were moderate (0.66-0.70); ICC for Session 2 was good (0.81). For the MER test, all ICCs for Session 1, Session 2, and All trials were rated moderate (0.69-0.74). Within-session variability was deemed to be of a good level (CV <5%) for both sessions of both tests, including a good level of variability across all trials.

Table 4.3 Within-session and all trials reliability and variability for the 30.5 m sprint test and the MER test

		Session 1 3 trials	Session 2 3 trials	All trials 6 trials
30.5 m sprint test (n = 14)	ICC	0.66	0.81	0.70
	CV%	3.1	2.3	2.9
MER test (n = 28)	ICC	0.69	0.74	0.69
	CV%	2.6	2.2	2.8

n = number of participants; ICC = intraclass correlation coefficient; CV % = coefficient of variation as percentage

The between-session reliability for the 30.5 m sprint test and the MER test are presented in Table 4.4. Between-session reliability for MEAN of both sprint tests revealed good ICCs (0.83) with low levels of variability (CV <5%) and small effect sizes (ES <0.1). Between-session reliability for BEST of both sprint tests showed moderate ICCs (0.71-0.72), also with low levels of variability (CV <5%) and small effect sizes (ES <0.1). No significant differences were observed between sessions.

Table 4.4 Between-session reliability for the 30.5 m sprint test and the MER test (mean ± SD)

		Session 1	Session 2	Cohen’s *d* Session 1-2	ICC Session 1-2	Between Session CV%	T-test
30.5 m sprint test (n = 14)	MEAN	6.83±0.37	6.87±0.40	0.09	0.83	1.9	NS
	BEST	7.04±0.38	7.02±0.41	0.07	0.71	2.4	NS
MER test (n = 28)	MEAN	7.25±0.33	7.28±0.33	0.09	0.83	1.6	NS
	BEST	7.44±0.34	7.44±0.34	0.004	0.72	1.9	NS

MEAN: mean of 3 trials; BEST: best of 3 trials; NS = not significant, p > 0.05

Results of both MSS tests for 64 participants is shown in Table 4.5. The MER test and 30.5 m sprint test results were significantly different for both best and mean MSS. Moderate agreement between the tests of different distances was found for both best and mean MSS (0.72-0.73), with very large effect sizes (0.78-0.84) between the different distances. Reported MSS speeds were higher for best compared to mean, with a 2.3% difference between best and mean for the MER test and 2.0% difference between best and mean for the 30.5 m sprint test.

Table 4.5 Between-test agreement for MSS tests of different differences (mean ± SD)

n = 64	MER test	30.5 m sprint test	Cohen's *d*	ICC MER-30.5 m
Best	7.38 ± 0.43	7.03 ± 0.41*	0.84	0.72
Mean	7.21 ± 0.43	6.89 ± 0.40*	0.78	0.73

Best: best of ≥ 2 trials; Mean: mean of 2 or 3 trials from a single test session; *MER test and 30.5 m sprint are significantly different (p <0.001)

4.4 Discussion

The aims of the present study were to examine maximal sprint speed in adolescent female soccer players and to investigate whether a previously recommended sprint-speed threshold used in previous studies of adolescent player match load based on adult data is appropriate to evaluate adolescent match-play. Secondary aims included evaluating the use MSS measured via timing gates and GPS, evaluating the reliability of two MSS tests of different distances, and to compare the use of a shorter soccer-specific sprint test distance to a longer flying MSS test. The speeds measured via timing gates are comparable to other reported adolescent speed data. Speeds measured via GPS are not comparable to speeds from TG splits over 10 m. Both the 30.5 m sprint and the MER tests reproduce results with good reliability. The MSS tests of different distances are not comparable and longer sprint distances are the most appropriate way to test MSS. Importantly, results from the speed tests demonstrate that the current cohort of U16 player participants have sprint speed ability similar to previously assessed adult sprint speed ability and that the previously used sprint-speed threshold can appropriately be applied to adolescent match-play analysis.

4.4.1 Measures of speed via TG with comparison to adolescent female data

Speeds measured via timing gates were similar to previously reported speeds over the same distances in similar cohorts. In the current study, participants had a mean 0-10 m sprint speed of 5.26 $m \cdot s^{-1}$, the same as a matched cohort of U16 players from an RTC (Emmonds et al., 2020) and similar to U15 and U17 national players (5.24 – 5.35 $m \cdot s^{-1}$) (Datson, 2016), though higher than the 4.99 $m \cdot s^{-1}$ reported from selected players for a soccer talent ID camp (Hoare & Warr, 2000). The similarities in 0-10 m speeds also reflect the agreement of 0-9.1 m sprint speeds in a cross-sectional study of 12 – 21 year olds where no significant differences were observed for this split across all age groups (Vescovi et al., 2011). Current study participants also had a higher 0-20 m sprint speed than selected players from the talent ID camp (5.95 v 5.76 m·s^{-1}) (Hoare & Warr, 2000) and lower speed than similar-age national players (5.95 v 6.04-6.17 m·s^{-1}) (Datson, 2016) although these speeds, particularly comparing with U15 national players, are not dissimilar. These differences potentially reflect the performance differences between players, as selected players were tested as part of a talent ID camp and were not in regular soccer-specific training, while national players are one level above the current participants in the FA development pathway. In comparing results to adult female players at or near the professional level, 0-10 m sprint speeds were higher in the current study (5.26 m·s^{-1}), for U16 players from a similar RTC (5.26 m·s^{-1}) (Emmonds et al., 2020), and in U15 and U17 national players (5.24 – 5.35 m·s^{-1}) (Datson, 2016) compared to high-level adult players (5.0 m·s^{-1}) (Vescovi, 2012b). Sprint speeds over 0-20 m were comparable between the current study and high-level adult players (5.95 v 5.89 m·s^{-1}) (Vescovi, 2012b).

It was not possible to accurately compare intermediate flying 10 m splits with the current study as timing gate times for 10-20 m flying splits were not reported in adolescent studies. Speeds of 6.59 m·s^{-1} from similar sprint distances (9.1-18.3 m) were reported for ages 14 – 17 (Vescovi et al., 2011), lower than the flying 10 m split in the current study (6.96 m·s^{-1}). Flying 10 m split speed in the current study is more comparable to the 7.00 m·s^{-1} over 18.3-27.4 m in the same study in adolescent female players (Vescovi et al., 2011), though the difference in split distances between studies makes this a cautious comparison. Flying 10 m splits in the current study (6.96 m·s^{-1}) were lower compared to high-level adult female players (7.19 m·s^{-1}) (Vescovi, 2012b), although considering the lower 0-10 m and 0-20 m splits in high-level adult players compared to the current study, this is surprising; the difference could be explained by high-level adult players undertaking a rapid acceleration after the initial 10 m. In total, the sprints speeds measured by timing gates in the current study reflect previous research in adolescent female sprint ability and provide coaches and analysts with additional information for 10 m flying sprint speeds for U16 players.

4.4.2 Comparison of GPS and TG speed measures

A significant difference was observed between maximal sprint speeds measured concurrently via GPS and TG. Although a large positive correlation was observed between the measurements, TG tended to underestimate sprint speed compared to GPS. The large correlation between TG and GPS in the current study are similar to correlations of 15 Hz GPS to timing gates over a similar sprint distance of 10 m (r = 0.64 – 0.76) (Johnston et al., 2014), reflecting results of validity studies of GPS as a measurement of speed (Coutts & Duffield, 2010). The trend of underestimation is likely from the methods of measurement where timing gates provide an average speed over a known distance in metres; GPS measures displacement in smaller quantities depending on the sampling rate. Although TG are used to test MSS and have been used as criterion measures in validity studies previously (Coutts & Duffield, 2010; Johnston et al., 2014), the difference in methods of measurement between devices and subsequent results from concurrent sprint measures in the current study show MSS measured via GPS and TG are not comparable over short distances.

4.4.3 Reliability and comparability of 30.5 m sprint and MER tests

There are few published studies on the test-retest reliability of linear sprint speed tests using GPS, limiting comparison to the current study. The within-session CVs of both the 30.5 m sprint and MER tests (2.2-3.1%) for both sessions were higher than a similar study testing peak speed using GPS between two 30 m linear sprint trials in the same session (0.78%) (Waldron et al., 2011), though the within-in session reliability of the current study is good. A decrease in CVs were observed between Session 1 and Session 2 for both tests, along with an improved ICC from moderate to good (0.66 to 0.81) in the 30.5 m sprint test. The improvement between sessions for both tests suggests a potential small habituation effect. The CVs for all trials are similarly good for both the 30.5 m sprint and MER tests (2.9% and 2.8%, respectively). Between-session CVs for MEAN and BEST for both tests were also very good (1.6-2.4%), with lower CVs and large ICCs for MEAN of both tests indicating increased relative reliability of MEAN over BEST. Between-session CVs for the current study are higher than between-session CV in a study testing peak speeds of a single repeated 30 m sprint ability test one week apart (1.2%) (Barbero-Álvarez et al., 2010). In comparing the means of each test between sessions, a smaller effect size was observed between sessions for the BEST of both tests compared with MEAN. Together, these results indicate that both the 30.5 m sprint and MER tests are reliable for testing sprint speeds. The MEAN of the sprint tests is more reliable for monitoring player sprint speeds over time, and the use of BEST provides a stronger test when assessing the mean sprint speeds of a population and can be used to determine sprint speed thresholds in match-play.

Although moderate correlations (ICC: 0.72-0.73) were observed indicating a relationship between the 30.5 m sprint and MER tests, significant differences and very large effect sizes (0.78-0.84) were observed between the longer and shorter sprints, demonstrating that the sprint tests are not comparable and players require longer distances >30 m to reach MSS (Bradley & Vescovi, 2015) as players are still accelerating through 20 m. However, the shorter sprint based on sprint distances in match-play has been shown to be a reliable measure of sprint speed using GPS. This provides an additional tool for coaches and performance analysts to be able to compare GPS-tested maximal sprint speeds over match-specific distances with sprint speeds over similar distances during match-play.

4.4.4 Sprint-speed threshold for adolescent female soccer players

This study investigated the sprint speed ability of U16 female soccer players in relation to a recommended sprint-speed threshold of 5.56 $m \cdot s^{-1}$ (Bradley & Vescovi, 2015). The sprint-speed threshold was previously utilised in assessing match load of adolescent players but is based on adult female data using 80-85% of MSS tested over >30 m (Bradley & Vescovi, 2015). Using data from the current study to determine a sprint-speed threshold following the same method, the threshold for U16 players using BEST MSS from the MER (7.38 $m \cdot s^{-1}$) would be 5.9 – 6.27 $m \cdot s^{-1}$. This is higher than the 5.56 $m \cdot s^{-1}$ sprint threshold used in other studies of adolescent female match-play (Ramos et al., 2019; Vescovi, 2014) and could be considered as a sprint-speed threshold determined by GPS for use with GPS match load analysis. In comparison, as the sprint threshold in adolescent female studies was in part determined by MSS tested using timing gates, use of the flying 10 m split speeds from timing gates in the current study (6.96 $m \cdot s^{-1}$) would yield a threshold of 5.57 – 5.92 $m \cdot s^{-1}$, which aligns closely with the previously utilised 5.56 $m \cdot s^{-1}$ threshold. The results in the current study demonstrate that the current cohort of U16 female soccer players possess similar sprint speed ability to adult female players and would be capable of attaining fixed, defined sprint speeds during match-play. Importantly, the use of the 5.56 $m \cdot s^{-1}$ sprint threshold determined from adult female data with an adolescent population ≥14 years of age would not underestimate sprinting movement in match-play and would allow for appropriate comparison of match loads with age-matched cohorts.

4.4.5 Considerations in selecting a fixed sprint-speed threshold

In determining a threshold using GPS-derived MSS from >30 m in the current study, the threshold could be higher for the current cohort compared to the previously utilised 5.56

$m \cdot s^{-1}$ threshold. However, using a higher threshold would present further challenges as a current issue in the literature is the lack of standardised speed thresholds for match load analysis (Hodun et al., 2016), which precludes comparison between the literature and formation of normative data that is limited in adolescent female soccer. Speed threshold considerations are expounded in Chapter 2 (Section 2.2.2 Speed Thresholds). Advantages of utilising previously recommended and player-independent sprint-speed thresholds to examine match load include allowing for comparison between players, positions, teams (Hunter et al., 2015) and previous studies (Datson, 2016) and for determining mean match loads of a specific population (Malone et al., 2017). However, the use of a fixed sprint-speed threshold does bring considerations for subsequent analysis of match load. Fixed sprint-speed thresholds will not account for individual performance capacity (Hunter et al., 2015) and may not provide additional individual-specific information regarding individual match loads (Lovell & Abt, 2013). Fixed-speed thresholds will not account for in-season variations of sprint speed ability (Malone et al., 2017) noted in adolescent female players (Emmonds et al., 2020; Taylor et al., 2012), however fixed-speed thresholds may be beneficial for tracking in-season variations. While these limitations are acknowledged, use of individualised sprint-speed thresholds are limited in other ways including potential errors in interpreting relative high-speed movement (Hunter et al., 2015) and inability to distinguish between player performance (Goto et al., 2015). The utility of fixed and individualised speed thresholds requires further research (Malone et al., 2017).

4.5 Summary

Participants in the current study demonstrated similar sprint capabilities to age-matched female soccer players. To the author’s knowledge, this is the first study to assess the test-retest reliability of MSS using GPS in female soccer players. Both the 30.5 m sprint and the MER tests are reliable and can be used to monitor player sprint ability over match-specific distances and for MSS, respectively, with the use of GPS. The mean of 3 trials should be used for monitoring sprint speed results over time as the mean of 3 trials for both tests demonstrated higher relative reliability than best of 3 trials. The lower effect size observed between the means for the cohort for best of 3 trials in both tests suggests the best of 3 trials should be used when assessing sprint speed in a population. Although a sprint distance of >30 m is needed to test player MSS, the shorter match-specific sprint test using GPS is reliable and provides a further analysis and monitoring tool for training development. Tested sprint speed using both GPS and timing gates show that U16 players are capable of reaching sprint speeds similar to adult female data (Vescovi, 2012b, 2012a) used to determine the sprint-speed threshold utilised in previous female adolescent match analysis (Ramos et al., 2019; Vescovi, 2014). Therefore, this sprint-speed threshold can be appropriately used for adolescent match load analysis to quantify sprint-speed movement.

CHAPTER 5

Match Load for Adolescent Female Soccer: Comparison between full-match and substitution match-play

5.1 Introduction

The previous chapter evaluated the sprint speed ability of adolescent female soccer players and investigated the appropriateness of using previously established adult female soccer sprint-speed threshold (Bradley & Vescovi, 2015) for adolescent female players. Adolescent female soccer players were found to have sprint speed ability beyond the established sprint-speed threshold, justifying the use of the sprint-speed threshold established for adult female players to evaluate match load in adolescent female players. With the understanding that established high-speed activity zones may be used for adolescent players, the evaluation of match load for adolescent players may now be undertaken. Understanding match load is important to developing appropriate training regimes and monitoring fatigue (Carling et al., 2008). However, match load data from adolescent female soccer players is limited, currently consisting of two studies from high-level U15 – U17 domestic players (Vescovi, 2014) and U17 international players (Ramos et al., 2019), which are reviewed in Chapter 2 (Section 2.3 Match load in female soccer). Further data is needed to better understand adolescent female match loads.

A key part of match load analysis, high-speed activity (HSA) is an important component of soccer performance and indicator of player aerobic capacity (Krustrup et al., 2005; Ramos et al., 2019) that has been used to indicate fatigue onset during match-play (Mohr et al., 2003), with 1st to 2nd half reductions in high-speed and sprint-speed running noted in the literature for adult female soccer players (Andersson et al., 2010; Datson et al., 2017; Hewitt et al., 2014; Mara et al., 2017a; Mohr et al., 2008; Ramos et al., 2017; Strauss et al., 2019; Vescovi, 2014). For adolescent female players, reductions in HSA between match halves were observed for U16 and U17 players with inverse increases in low-speed running; however, HSA reductions for U15 players were not clear (Vescovi, 2014). Between-half differences were not evaluated in Ramos et al (2017) underscoring the limited data available in the literature in this population. Further understanding of between-half reductions in match loads would be useful to coaches and practitioners to monitor the occurrence of fatigue onset in match-play in adolescent female players.

However, use of speed zones to categorise high-speed activity in match-play may not account for short-duration maximal efforts because they do not reach high-speed thresholds (Varley & Aughey, 2013). To account for these short maximal efforts, motion analysis may include evaluating accelerations and decelerations to provide further insight into match load, particularly as they relate to higher energy cost compared to running at constant speed (di Prampero, 2005; Osgnach et al., 2010) and eccentric muscle activity that may impact on fatigue (Proske & Morgan, 2001). In adolescent female soccer, Ramos et al (2017) reported acceleration and deceleration counts in match load, with mean accelerations ranging from 149.7 – 199.0 across all U17 positions and mean decelerations ranging from 85.8 – 122.0 across all U17 positions over 90-minute matches. However, between-position and between-half analyses were not conducted. Further, this single study including adolescent acceleration and deceleration match load in adolescents was at an international level of match-play which may not provide an appropriate indicator of expected acceleration and deceleration load for non-international adolescent players.

Both studies of adolescent match load reported positional differences similar to studies in adult female soccer, namely that Midfield players completed more total distance compared to Defenders (Andersson et al., 2010; Datson et al., 2017; Gabbett & Mulvey, 2008; Hewitt et al., 2014; Vescovi, 2014), and Forward players were observed to sprint more compared to Midfield and Defender players (Gabbett & Mulvey, 2008; Mohr et al., 2008; Vescovi &

Favero, 2014). In Vescovi (2014), total distances were also shown to reduce from 1st to 2nd half by approximately 100 – 150 m for all playing positions suggesting that, despite positional differences, performance reductions indicative of fatigue may occur in any playing position. While both studies of female adolescent match-play provide valuable information to coaches and support staff that can help inform good training practices, neither study includes the evaluation of the match loads of substitutes.

Youth soccer rules allow for unlimited substitutions in non-cup competition matches (The English Football Association, 2017a). In female NCAA college soccer where frequent substitutions are also allowed, large differences in time played as a result of substitutions have been found to impact on observed match loads (Gentles et al., 2018). Data on substitution match loads are limited in both male and female soccer. Studies of substitutes in female soccer found substitutes perform higher work rates and complete higher relative distances per minute above HSA thresholds compared to full-match players (Hills et al., 2018). Additionally, the data reviewed suggests substitutes maintain physical intensity or have higher outputs when entering or returning to match-play (Vescovi & Favero, 2014). However, to date, no study has evaluated the match loads of substitutes in unlimited substitution conditions nor compared full-match loads with substitution match loads in adolescent soccer.

In consideration of the gaps in the literature — the limited available data of adolescent female match load and lack of data regarding substitute match load in youth soccer — the aim of this study was to investigate adolescent female soccer match loads including substitute match loads. Particular aims included assessing position-specific match loads, with focus on sprint-speed and high-speed running and acceleration and deceleration to examine high-speed and high-intensity activity, indicators of fatigue onset within match-play, and the effects of substitution on match load.

5.2 Methods

5.2.1 An experimental approach to the problem

To evaluate the match loads of adolescent female soccer players, external and internal match load were quantified for 36 participants over 20 matches. High-speed running and acceleration and deceleration were considered in addition to other match variables for each position classification. Full-match (Chapter 5, Section A) and substitutes (Chapter 5, Section B) condition match loads and differences in 1st and 2nd half match loads were evaluated. Further, full-match and substitute conditions were compared (Chapter 5, Section B). The aims of this study fulfil research objective 2 to investigate match loads in adolescent female soccer and research objective 4 of this thesis, to explore differences in match loads between substitutes and full-match players in consideration of unlimited substitution rules.

5.2.2 Participants

Thirty-six participants from two Regional Talent Clubs (RTCs) U16 teams took part in this study. Participant anthropometric measurements are shown in Table 5.1. Participants had an average football training age of 9 (± 2.5) years. Ten participants additionally trained with their national teams at various points in the season, 14 participants took part in at least one other sport on an average of 1.25 hours per week, and all participants had formal physical education classes at school an average of 3 hours per week.

Table 5.1 Participant anthropometrics

Number of participants	36
Age (years)	15.03 ± 0.64
Weight (kg)	56.2 ± 6.5
Height (cm)	161.9 ± 5.3
Sitting Height (cm)	83.4 ± 3.8
Leg length (cm)	78.5 ± 4.0
Age at Peak Height Velocity (years)	12.9 ± 0.4
Maturational Offset (years)	2.3 ± 0.6

The University of Gloucestershire Research Ethics Committee evaluated and approved the protocols in these studies. Coaches and the respective heads of the RTCs were informed of the procedures for match testing and consented to game data collection. Participants and their parent or guardian gave written consent for the participant’s anonymised data to be used in this study. All data were stored and processed in accordance with the General Data Protection Regulation (GDPR). Participants had no RTC-scheduled activities on Friday evenings, and played all matches on Saturday mornings or afternoons. No restrictions were placed on training or diet as the purpose of the study was to evaluate match load in the course of a normal season. For the 24 hours prior to a match, participants were provided RTC-developed guides and were instructed by coaches and RTC support staff to use rest and recovery strategies, to avoid strenuous activity before a match, and to have an appropriate diet for pre-match preparation. Each team used their own standard warm up prior to each match (Chapter 3, Table 3.5); substitutes warmed up individually. Only participants who were deemed fit to fully take part in a match by RTC medical staff were included in the study.

Twenty matches resulting in 217 match observations, including 92 full-match observations and 104 substitution observations, were collected. Although some matches were cup matches under limited substitution rules, the aim of the study was to examine and compare full-match (FULL) and substitute (SUB) match loads; as such, substitutions made under limited substitution rules were not differentiated and all substitution match observations are considered together. Match data were analysed per playing position (Forward, Midfield, and Defender); goalkeepers were not included in the study due to the specific nature of the position. Participants did not always specialise in a playing position, resulting in match observations (n = 21) where participants changed positions during a match (i.e. Midfield to Defender); these match observations were excluded for the purposes of studying match loads. Also due to participants not specialising in a position, some participants for FULL and SUB are counted in more than one playing position category, resulting in the number of players exceeding the number of study participants.

5.2.3 Match-play and data collection

Match data were collected using GPS (15 Hz GPSports HPU system, Canberra, Australia) and HR monitors (Polar T34, Polar, Kempele, Finland). Match day procedures for participants are described in detail in Chapter 3, including the use of GPS and HR monitors (Chapter 3, Section 3.3.1 GPS in matches), and the description of matches observed (Chapter 3, Section 3.1.4 Testing locations and conditions).

Matches consisted of two 40-minute halves with a 10-minute half time, with start and end times for each half noted by the researcher using a GPS-synced watch (Vivoactive 3, Garmin, Olathe, KS, USA). Previous research in team sports suggests use of active match-play time, compared to time-on-pitch, is the most accurate method to evaluate match loads (White &

MacFarlane, 2013). Periods of brief inactivity such as when the ball is out of play are a normal part of match-play. However, injury time or other excessive delays can occur in match-play during which players are inactive on the pitch and match-play time is lost. Referees allocate stoppage time to offset lost match-play time (“Law 7 - The Duration of the Match,” 2019), resulting in match halves longer than 40 minutes. Given that stoppage time is provided to offset these inactive periods, stoppage time is not considered as additional time for full-match participants, participants who completed an entire match half, or participants substituted onto the pitch before an inactive period. If a participant was substituted onto the pitch after an injury period, time played for that participant was noted to include stoppage time as illustrated in Figure 5.1. No matches observed went into extra-time and all matches were fully refereed.

Figure 5.1 Illustration of differences in time played between substitutes with sample player time-on-pitch compared to active match-play when substituted before or after an inactive injury period. Time played for each match observation includes only active match-play.

After each match, GPS units were placed into the GPS system docking station. Files were transferred from the docking station to a computer using the TeamAMS software (version R1 2016.7). Match files were cut to only include a participant’s time on the pitch with active match-play time used for analysis. Match-play variables as defined in Chapter 3 (Section 3.3.3 GPS data processing and variables) were recorded from the software. Variables for each match file are shown in Table 5.2. Running and sprinting thresholds were set according to Bradley and Vescovi (2015) as evaluated for use in adolescent female soccer in Chapter 4 of this thesis. It was not possible to conduct a maximal aerobic fitness test with participants; instead maximal HR was estimated using the Tanaka equation ($HR_{max} = 208 – 0.7*age$) as a recommended estimation equation specifically for youth (under 18 years of age) maximal HR (Cicone et al., 2019).

Table 5.2 Match variables provided by the TeamAMS software and calculated for the purpose of match analysis

Variable	Unit of measurement
Total distance (TOTAL)	m
Time played	min
Work rate (WR)	$m \cdot min^{-1}$
Sprint distance ($\geq 5.6\ m \cdot s^{-1}$) (SPR)	m
High-speed running distance ($\geq 4.3, < 5.6\ m \cdot s^{-1}$) (HSR)	m
Low-speed running ($< 4.3\ m \cdot s^{-1}$) (LOW)	m
Average speed (AVG)	$m \cdot s^{-1}$
High-speed activity (HSA) ($\geq 4.3\ m \cdot s^{-1}$)	m
# of sprint-speed efforts (defined by sprints $\geq 5.6\ m \cdot s^{-1}$ for ≥ 1 s duration) (SSE)	
# of high-intensity accelerations (defined by acceleration $> 2.0\ m \cdot s^{-2}$ for ≥ 1 s duration) (HIA)	
# of repeat HIA (occurring < 30 s) (REPEAT)	
# of accelerations ($> 1.0\ m \cdot s^{-2}$) (ACCEL)	
# of decelerations ($< -1.0\ m \cdot s^{-2}$) (DECEL)	
Average heart rate (average HR)	beats per minute

CHAPTER 5 – Section A

Analysis of match load in full-match conditions

5.3 Section A – Methods

Match files were designated as full-match (FULL) if a participant completed ≥75 minutes in a match without a return to match-play. This designation was made in consideration of one example in the current study where observed time played for one participant was 73 minutes, however the participant had been substituted off the pitch for 10 minutes during the 2nd half and returned after an injury time, resulting in additional active match-play. This reflects similar research of full-match movement loads where youth players completing 90% of a match were considered for full-match analysis (Strøyer et al., 2004).

Occurrences of poor signal from the HR monitors affecting the calculation of average HR were noted in some match observations. Average HR in match files that were affected were not used for the purposes of this study, resulting in a reduced number of match observations for this variable. For purposes of clarity, average HR was considered separately from the other match variables. Tables 5.3 and 5.4 provides a summary of analyses, number of participants, and number of match files for FULL conditions and for between-half comparison analyses for FULL conditions, respectively. In all results tables, the number of match files for each condition are given.

5.3.1 Evaluating match loads in full-match conditions

To evaluate full-match total match loads in adolescent female soccer players, data were compared in several ways. First, total match load was compared between the three position categories for FULL match observations using raw data. To examine the proportion of match load in HSA and low-speed zones, the percentage of TOTAL distance completed in the SPR and HSR speed zones (%SPR and %HSR) and LOW speed zone (%LOW) and the percentage of HIA that were repeat HIA (%REPEAT) are compared between positions within FULL conditions. It was hypothesised that a decrease in match load would be observed from 1st to 2nd half. To test this hypothesis, two analyses were undertaken. (1) Raw GPS variables were compared within-participant between 1st and 2nd half for each playing position using FULL match observations. (2) Average HR as a measure of internal load was compared between 1st and 2nd half periods. Although WR is a relative measure of TOTAL distance, it is a commonly used measure in team sports to evaluate match loads and so is included in raw data results.

5.3.2 Statistical analysis

Statistical analysis was conducted using Excel (Microsoft, Redmond, WA) and SPSS (Version 24, SPSS Inc., Chicago, IL). Data are presented as mean ± standard deviation (SD). All data were assessed for normality using skewness and kurtosis; values for asymmetry and kurtosis between -2 and +2 are considered acceptable to prove normal distribution (George & Mallery, 2010). Levene's test was used to assess the assumption of equal variance for each variable. Where reported, Cohen's *d* for effect size was considered small, moderate, large, very large, and extremely large with values greater than 0.1, 0.3, 0.5, 0.7, and 0.9, respectively (Hopkins et al., 2009). Effect sizes for ANOVAs are reported as partial eta squared (η^2) and interpreted as small ($0.01 \leq \eta^2 < 0.06$), moderate ($0.06 \leq \eta^2 < 0.14$), or large ($\eta^2 \geq 0.14$) (Cohen, 1988).

5.3.2.1 Statistical analysis to evaluate total match loads within full-match conditions

A one-way ANOVA was used to analyse between-position differences using raw data for FULL match observations. Percentages of total distance for %SPR, %HSR, and %LOW and percentage of HIA for %REPEAT were calculated and a one-way ANOVA was performed to analyse between-position differences for percentage variables. Post hoc analysis was performed with Bonferroni adjustment if equal variances were assumed and Dunnett T3 adjustment if equal variances were not assumed. In the event of a possible violation of assumption of normality, data were re-analysed using the nonparametric equivalent of the test which did not change results.

5.3.2.2 Statistical analysis to evaluate differences in 1st and 2nd half match loads within full-match conditions

To compare within-participant differences between the 1st and 2nd halves for FULL match observations, paired t-tests were used to compare the means for each variable. Paired t-tests were also used to compare 1st and 2nd half average HR. In the event of a possible violation of assumption of normality, the nonparametric equivalent of the test was used which did not change results; one exception occurred for DECEL for FULL Defender and the significant nonparametric result was used as noted in the results. Coefficient of variation (CV) as a percentage was calculated as CV = (SD/mean)*100. Statistical significance was accepted at $p < 0.05$.

Table 5.3 Summary of analysis, number of participants, and number of match files for evaluating match loads in full-match conditions

	FULL total match load		
Comparison	Between positions		
Data	Raw		
Position	F	M	D
# of players	8	13	15
# of match observations	19	29	44

Table 5.4 Summary of analyses, number of participants, and number of match files for evaluating differences in 1st and 2nd half match loads in full-match conditions

	FULL 1st v 2nd half external match load			FULL 1st v 2nd half internal match load		
Comparison	Within-participant			Within-participant		
Data	Raw			Heart rate		
Position	F	M	D	F	M	D
# of players	8	13	15	5	10	14
# of match observations	19	29	44	9	18	35

5.4 Section A – Results

5.4.1 Match loads in full-match conditions

Raw data for all GPS variables for FULL total match load and between-position comparisons are shown in Table 5.5, including 95% confidence intervals to demonstrate the observed variation of match loads within a playing position. Midfield players covered greater TOTAL distance and LOW distance and subsequently had higher WR compared to Forwards and Defenders, with a large effect size (partial $\eta^2 = 0.204$) between positions. More distance above the sprint-speed threshold and more SSE efforts were completed in Forward match observations compared to Midfield and Defender match observations, with moderate effect sizes (partial $\eta^2 = 0.110$ and 0.125, respectively) observed for both variables between positions. In Forward match observations, participants completed more HIA and REPEAT efforts compared to Defenders, with large (partial $\eta^2 = 0.142$) and moderate ($\eta^2 = 0.120$) effect sizes, respectively between positions. Differences between positions for other variables were not significantly different. Acceleration and deceleration counts were similar between all positions.

In comparing percentage variables for LOW, HSR, and SPR distances and REPEAT as shown in Figure 5.2, between-position comparisons show lower percent LOW distances for Forward match observations compared to Midfield (extremely large effect size, $d > 0.9$) and Defender (very large effect size, $d > 0.7$). Forward match observations had significantly higher percent HSR compared to Midfield match observations (very large effect size, $d > 0.7$). Forward match observations also had a significantly higher percent REPEAT efforts compared to Defender match observations (extremely large effect size, $d > 0.9$). Forward match observations had higher percent SPR distances compared to Midfield and Defender with extremely large ($d > 0.9$) effect sizes for comparison with Midfield and very large with Defender ($d > 0.7$).

Table 5.5 Raw data for FULL match observations per playing position for all variables and one-way ANOVA results comparing playing position for each match variable

					Position Main Effect		Pairwise Comparison
		Forward	**Midfield**	**Defender**	F	(p-value)	(p-value)
		n = 19	n = 29	n = 44		partial η2	Cohen's *d*
TOTAL (m)	Mean ± SD	7801.8 ± 933.4	8388.8 ± 493.8	7601.5 ± 699.4	11.27	($p <0.001$)	M > F & D
	95%CI	7351.9 - 8251.6	8201.0 - 8576.7	7388.9 - 7814.2		$\eta^2 = 0.202$	($p = 0.017$ & $p<0.001$)
WR (m·min^{-1})	Mean ± SD	97.5 ± 11.7	105.1 ± 6.1	95.2 ± 8.8	11.41	($p <0.001$)	M > F & D
	95%CI	91.9 - 103.1	102.8 - 107.4	92.5 - 97.9		$\eta^2 = 0.204$	($p = 0.013$ & $p<0.001$)
SPR (m)	Mean ± SD	219.0 ± 84.4	123.5 ± 122.8	153.3 ± 84.2	5.49	($p = 0.006$)	F > M & D^{T3}
	95%CI	177.4 - 260.7	76.8 - 170.2	127.7 - 178.9		$\eta^2 = 0.110$	($p = 0.008$ & $p = 0.025$)
HSR (m)	Mean ± SD	643.4 ± 244.5	515.1 ± 247.8	504.2 ± 199.1	2.73	NS	
	95%CI	525.5 - 761.2	420.8 - 609.3	443.7 - 564.8			
LOW (m)	Mean ± SD	6939.3 ± 698.7	7750.2 ± 626.4	6944.0 ± 609.9	16.12	($p <0.001$)	M > F & D
	95%CI	6602.6 - 7276.1	7512.0 - 7988.5	6758.5 - 7129.4		$\eta^2 = 0.266$	($p < 0.001$ & $p < 0.001$)
SSE	Mean ± SD	13 ± 5	8 ± 7	9 ± 4	6.36	($p = 0.003$)	F > M & D
	95%CI	11 - 16	5 - 10	8 - 10		$\eta^2 = 0.125$	($p = 0.007$ & $p = 0.008$)
HIA	Mean ± SD	88 ± 30	76 ± 22	65 ± 19	7.35	($p = 0.001$)	F > D
	95%CI	74 - 103	67 - 84	59 - 71		$\eta^2 = 0.142$	($p = 0.001$)
REPEAT	Mean ± SD	40 ± 26	31 ± 15	24 ± 13	6.10	($p = 0.003$)	F > D

	95%CI	27 - 53	25 - 36	20 - 28		$\eta^2 = 0.120$	(p = 0.003)
ACCEL	Mean ± SD	287 ± 100	281 ± 96	264 ± 67	0.65	NS	
	95%CI	239 - 335	245 - 318	244 - 284			
DECEL	Mean ± SD	268 ± 112	264 ± 126	271 ± 84	0.04	NS	
	95%CI	214 - 322	216 - 312	245 - 296			

TOTAL = total distance (m); WR = work rate ($m \cdot min^{-1}$); SPR = sprinting distance $\geq 5.6 \ m \cdot s^{-1}$ (m); HSR = high-speed running distance $\geq 4.3 \ m \cdot s^{-1}$, $< 5.6 \ m \cdot s^{-1}$ (m); LOW = low-speed running distance $< 4.3 \ m \cdot s^{-1}$ (m); SSE = number of sprint-speed running efforts $\geq 5.6 \ m \cdot s^{-1}$ for ≥ 1 s duration; HIA = number of high-intensity accelerations efforts, $> 2.0 \ m \cdot s^{-2}$ for ≥ 1 s duration; REPEAT = number of HIA efforts that occur less than 30 s after a preceding effort; ACCEL = number of accelerations $> 1.0 \ m \cdot s^{-2}$; DECEL = number of decelerations $< -1.0 \ m \cdot s^{-2}$. 95%CI – 95% confidence interval for the mean. Partial η2 – partial eta squared for effect size. NS – p-value not significant. F – Forward, M – Midfield, D – Defender. ^{T3} = equal variances not assumed, Dunnett's T3 correction used for post hoc comparison; P-value is significant at $p < 0.05$.

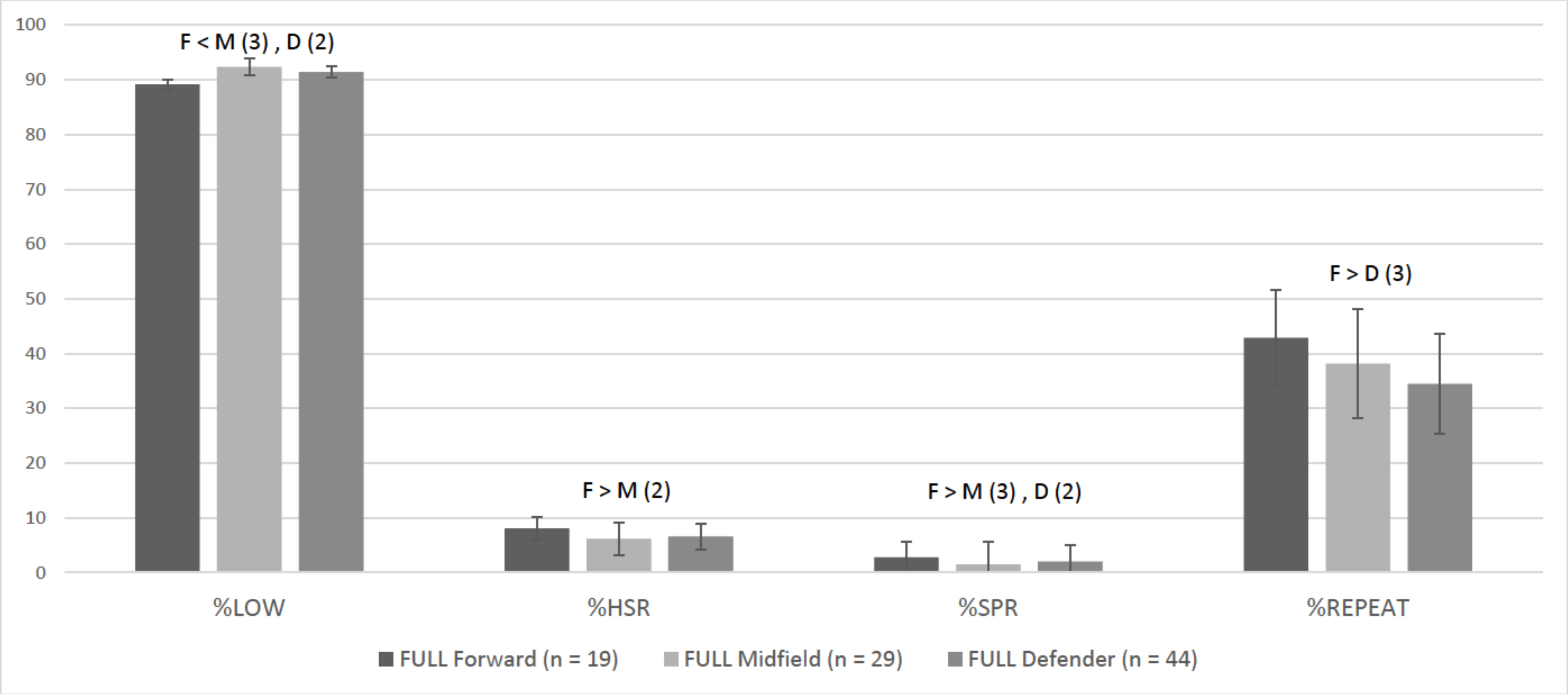


Figure 5.2 Percentage variables for LOW, HSR, and SPR distance and percentage of repeated HIA (mean ± SD) with effect sizes for between-position differences, from match observations as in Table 5.5. %LOW = percentage of total distance completed in LOW speed zone; %HSR = percentage of total distance completed in HSR speed zone; %SPR = percentage of total distance completed in SPR speed zone; %REPEAT = percentage of HIA efforts that are repeat efforts. Numbers denote effect size: 1 = large (>0.5), 2 = very large (>0.7), and 3 = extremely large (>0.9); < denotes significant difference between positions, $p < 0.05$; F = Forward, M = Midfield, D = Defender

5.4.2 Differences in 1st and 2nd half within full-match conditions

Raw data for 1st and 2nd half match loads for FULL conditions per playing position are shown in Table 5.6. Significant differences were observed between 1st and 2nd half with decreases into the 2nd half for TOTAL distance, LOW speed distance, AVG speed, and DECEL counts for all playing positions. Small effect sizes (*d* = 0.11 – 0.28) were observed for DECEL counts in all playing positions, with moderate to extremely large effect sizes (*d* = 0.43 – 1.0) for TOTAL, LOW, and AVG variables. For Midfield match observations, HSR distance and ACCEL counts were significantly lower in the 2nd half, both with moderate effect sizes (*d* = 0.31). Significantly lower ACCEL counts in the 2nd half were also noted for Defender match observations with a small effect size (*d* = 0.27). For all significant differences between 1st and 2nd halves, CVs were <15%. Large mean CVs between 1st and 2nd half are noted for SPR distance and SSE counts, ranging from 28.9 – 60.7% and 26.2 – 75.3% respectively. Large CVs and large standard deviations for these variables represent individual differences between 1st and 2nd half and the low distance and counts observed, or even increases from 1st to 2nd half in some cases.

Average heart rate for FULL match observations for 1st and 2nd match halves are shown in Table 5.7. Similar mean average heart rates are noted across playing positions with low (<5%) mean CVs between 1st and 2nd half. Paired t-tests revealed significant differences between match halves, with average heart rate decreasing from 1st to 2nd half. Effect sizes were moderate (*d* = 0.5) for Forward and Defender players, but extremely large (*d* = 0.99) for Midfield players. Percent of estimated maximal heart rates ranged from 86 – 93%, with Defender match observations showing lower percentages compared to Forward and Defender match observations.

Table 5.6 Raw data (mean ± SD) for 1st and 2nd half match loads per position for FULL match observations

	Forward				**Midfield**				**Defender**			
	n = 19				n = 29				n = 44			
	1st half	**2nd half**	CV	*d*	**1st half**	**2nd half**	CV	*d*	**1st half**	**2nd half**	CV	*d*
TOTAL (m)	4073.8 ± 515.0	3727.9 ± 511.4*	8.6	0.67	4349.2 ± 307.0	4039.6 ± 347.4*	6.7	0.94	3884.9 ± 378.1	3716.7 ± 403.1*	5.8	0.43
SPR (m)	114.1 ± 50.6	104.9 ± 53.6	28.9		62.6 ± 77.6	60.8 ± 54.9	60.7		77.1 ± 57.6	76.3 ± 42.1	46.0	
HSR (m)	340.8 ± 135.0	302.6 ± 122.2	14.0		278.3 ± 139.5	236.8 ± 127.7*	25.8	0.31	253.8 ± 124.3	250.4 ± 89.5	20.4	
LOW (m)	3618.9 ± 398.8	3320.4 ± 420.6*	9.1	0.73	4008.3 ± 354.7	3742.0 ± 378.7*	6.0	0.73	3557.8 ± 333.9	3395.1 ± 363.9*	5.9	0.47
SSE	7 ± 3	7 ± 3	26.2		4 ± 5	4 ± 4	75.3		5 ± 3	4 ± 2	39.9	
HIA	46 ± 16	42 ± 15	13.0		38 ± 12	37 ± 12	12.5		33 ± 11	32 ± 12	17.1	
REPEAT	22 ± 15	18 ± 13	31.4		16 ± 8	15 ± 8	24.9		12 ± 7	12 ± 8	37.0	
AVG	1.6 ± 0.2	1.5 ± 0.2*	8.9	0.5	1.7 ± 0.1	1.6 ± 0.1*	5.5	1.00	1.6 ± 0.1	1.5 ± 0.2*	5.7	0.63
ACCEL	149 ± 55	137 ± 47	10.0		148 ± 55	133 ± 42*	8.0	0.31	139 ± 34	130 ± 33*	11.2	0.27
DECEL	142 ± 62	126 ± 53*	12.9	0.28	141 ± 69	123 ± 58*	10.5	0.28	138 ± 42	133 ± 47*^{NP}	11.4	0.11

d = Cohen's d for effect size; CV = mean coefficient of variation as a percentage; * denotes significant difference between 1st and 2nd half, $p < 0.05$; ^{NP} = nonparametric test

Table 5.7 Average heart rate (bpm) (mean ± SD) for 1st and 2nd half in FULL match observations. 95% CI = 95% confidence interval. Within-participant measures for FULL are significantly different, p <0.02.

		FULL				
		n	1st half	2nd half	CV	Cohen's *d*
	Time played (min)		40 ± 0	40 ± 0		
Forward	Mean ± SD	9	180 ± 6	177 ± 6*	1.7	0.5
	95%CI		176-185	172-181		
	%maxHR		91 ± 2.9	89 ± 2.8		
Midfield	Mean ± SD	18	184 ± 5	178 ± 7*	2.5	0.99
	95%CI		185-189	177-187		
	%maxHR		93 ± 2.7	90 ± 3.4		
Defender	Mean ± SD	35	176 ± 9	171 ± 11*	2.8	0.50
	95%CI		176-187	166-180		
	%maxHR		89 ± 4.7	86 ± 5.5		

n = number of match observations; %maxHR = percentage of maximal HR; 95%CI = 95% confidence interval for the mean; CV = mean coefficient of variation as a percentage; *denotes significant difference between 1st and 2nd half, p <0.05

5.4.3 Summary of full-match condition results

Overall, Midfield players were observed to have higher TOTAL distance, LOW distance, and higher WR compared to Forward and Defender players. Forward players were observed to have higher SPR distances and more SSE counts. Forward players also had lower proportions of LOW distance and higher proportions of SPR distance compared to other positions, as well as higher proportions of HSR compared to Midfield players. All positions had similar ACCEL and DECEL counts. In comparing 1st and 2nd half match loads, there were observed decreases in the 2nd half in TOTAL distance, LOW distance, AVG speed, and DECEL counts for all positions. Midfield players also observed decreases in HSR distance, and both Midfield and Defender players observed decreases in ACCEL counts. In comparing average HR from 1st to 2nd halves, significant differences were observed between match halves with decreased average HR for all positions.

5.5 Section A – Discussion

5.5.1 Evaluation of full-match conditions in adolescent female soccer match-play

5.5.1.1 Match loads in full-match conditions

This study provides further insight into match loads for adolescent female soccer players under full-match conditions. Total mean distances for all playing positions in the current study (7601.5 – 8388.8 m) were similar to those previous research in adolescent female soccer (7779 – 8449 m) (Vescovi, 2014) in three age groups (U15 – U17). Players in the current study had higher total distance per time played compared to international U17 players in Ramos et al (2017) as international players had 10 extra minutes per match, shown in higher WRs in the current study. SPR distance, HSR distance, and LOW distance in the present study were also similar to Vescovi (2014) and appear higher compared to international players in Ramos et al (2017), with extra match time in international soccer taken into account. Total speed-based match loads for full-match players in the current study are in general agreement with previous investigations of adolescent female soccer match loads at domestic level, though appear to have higher-intensity match loads compared to adolescent players at an international level. This may reflect a lack of player development, similar to NCAA women's soccer players noted to struggle when attending international camps due to a lack of full-match experience in college soccer (Favero et al., 2015); in this sense, adolescent players observed at international level may have only developed the match load abilities of matches played within shorter times. This may also reflect a different style of play within a single team as observed in Ramos et al (2017).

5.5.1.2 Positional differences in full-match conditions

Position-specific loads in the current study also demonstrated similar patterns to previous investigations in female soccer (Andersson et al., 2010; Datson et al., 2017; Gabbett & Mulvey, 2008; Hewitt et al., 2014; Vescovi, 2014). The current study partially confirms observations in previous investigations that found Midfield covered greater TOTAL distance compared to Defender players but not Forward players (Andersson et al., 2010; Datson et al., 2017; Gabbett & Mulvey, 2008; Hewitt et al., 2014; Vescovi, 2014). By contrast, match observations in the current study show Midfield players recorded more TOTAL distance and LOW distance compared to both Forward and Defender as well as higher WRs compared to both. As in other investigations (Gabbett & Mulvey, 2008; Mohr et al., 2008; Vescovi & Favero, 2014), observations in the current study show that Forward players completed greater SPR distances compared to Midfield and Defender players. Forwards also completed more SSE compared to both playing positions. In some studies, only Defender players (Mohr et al.,

2008) or Midfield players (Vescovi, 2014) were observed to have significantly fewer SSE or less SPR distance compared to Forward players, which again might reflect different playing styles within a team. In the current study, Forward players were observed to spend a higher proportion of total distance above the SPR threshold compared to Midfield and Defender, respectively. Forward players also had a higher proportion of distance in the HSR speed zone compared with Midfield, with an inversely lower proportion of total distance in the LOW speed zone compared with Midfield and Defenders. Together with previous studies, these findings further highlight the importance of sprint-based match load specific to the profile of Forward players. This has implications on position-specific training that should include more sprint-based work for Forward players and an emphasis on aerobic work for Midfield players due to higher work rates and greater distances completed at lower speeds.

5.5.1.3 HIA, ACCEL, and DECEL in full-match conditions

The results of the current study included new insights into HIA, ACCEL, and DECEL counts for adolescent female soccer players. Relative HIA efforts in the current study ranged from 0.8 – 1.1 per minute. Though comparable data is not available for adolescent female soccer players, investigations in international adult female soccer using a similar HIA threshold (> 2.26 $m \cdot s^{-2}$) reported higher relative HIA efforts of 1.78 per minute (Meylan et al., 2017; Trewin et al., 2018b), which might be expected with older age groups and higher competition levels, similar to higher HSA in higher competition levels and older age groups as previously investigated (Andersson et al., 2010; Mohr et al., 2008; Ramos et al., 2019). For positional differences, higher numbers of HIA and REPEAT efforts were observed in Forward match observations compared to Defender, which aligns with higher observed sprint-speed counts and more sprint-speed distance in Forward players.

A study in international female soccer noted a large difference between relative SSE (> 5.55 m·s^{-1}) and HIA counts (> 2.26 m·s^{-2}) (Trewin et al., 2018b). Although relative SSE and relative HIA in the current study are respectively lower compared to the same variables in Trewin et al (2018b), a similarly large difference between SSE and HIA of 82 – 89% is shown in the current study. Large differences (80%) between SSE and HIA have also been observed in men's professional soccer (Varley & Aughey, 2013). Large differences between counts of high-speed motion and high-intensity acceleration underscore the need for acceleration and deceleration in match load descriptions in addition to speed-based measures. The higher count of SSE and HIA efforts in international players demonstrate the level of play that adolescent players should develop over time in order to play at higher competition levels. Data in the current study provide new information for expected match loads and further information for training development in adolescent female soccer with regards to high-intensity movement that might occur below sprint-speed thresholds.

Of further interest is the observation from the present data that ACCEL and DECEL counts were similar across all playing positions. The finding is different to the positional differences noted in Ramos et al (2017) for international players including U17, where ACCEL and DECEL using the same threshold as the current study (±1.0 m·s^{-2}) vary across playing positions which may be a result of differing playing styles and positional expectations from coaches (Ramos et al., 2019). ACCEL and DECEL counts were also higher in the current study across all playing positions compared to international players (Ramos et al., 2019) despite 10 minutes less time played per match in the current study. A similar investigation of ACCEL and DECEL in domestic professional female soccer found no positional differences in general acceleration and deceleration counts (Mara et al., 2017b), though a higher threshold was used (±2.0 $m \cdot s^{-2}$) that aligns to the threshold for HIA in the current study. However, Mara et al (2017b) noted positional differences when accelerations and decelerations are further categorised by starting and ending speeds, with Forward players performing more accelerations starting and ending at high speed and Defender players performing fewer leading accelerations starting at higher speed. The findings in the current study will be pertinent to the position-specific development of training programming in conjunction with speed-based differences. While acceleration and deceleration training could benefit all playing positions, acceleration and deceleration training for Forward players might focus on developing acceleration to attain sprint speeds and deceleration to slow from sprint speeds. Similarly, Defender players could benefit from an additional emphasis on acceleration to achieve short, sub-sprint speed movement.

Where international players (Ramos et al., 2019) had fewer observed DECEL compared to ACCEL across all playing positions, the current study observed similar numbers of ACCEL and DECEL. Similar numbers of ACCEL and DECEL could be expected as decelerations require prior accelerations (Hewit et al., 2011; Newans et al., 2019). Research in men’s professional soccer observed similar numbers between ACCEL and DECEL using a lower threshold of ±0.5 $m \cdot s^{-2}$ (Russell et al., 2016) and ±1.0 $m \cdot s^{-2}$ (Akenhead et al., 2013), respectively. However, varying thresholds, GPS systems, and software were used to determine ACCEL and DECEL, where smoothing methods might affect the magnitude of accelerations and decelerations observed and subsequent ACCEL and DECEL counts (Varley & Aughey, 2013); as such these comparisons are cautious. It seems appropriate that similar numbers between ACCEL and DECEL are observed in match-play as shown in the current study. However, further research is warranted utilising similar motion analysis and data processing methods to provide a better understanding of acceleration and deceleration match loads across different groups. To the author's knowledge, this is the first study to report on the acceleration and deceleration profiles of domestic adolescent female soccer players.

Generally, the current study supports the match load characteristics observed in full-match conditions in adolescent female soccer, along with general positional differences observed in female soccer, namely that Midfield players have higher match loads in total distance and work rate and Forward players have higher match loads above sprint-speed thresholds. Although speed-based match loads were position-specific, acceleration and deceleration were similar between positions. These match load profiles provide further information to coaches and performance specialists to assist in developing appropriate training in adolescent female soccer, particularly with regards to preparing players for position-specific match loads.

5.5.2 Differences in 1st and 2nd half match loads for full-match conditions

Differences between 1st and 2nd half match loads for full-match conditions are similar across all playing positions with significant decreases in TOTAL distance, LOW speed distance, and AVG speed. In contrast to previous literature where decreases in HSA distances were observed from 1st to 2nd half (Andersson et al., 2010; Datson et al., 2017; Mara et al., 2017a; Ramos et al., 2017; Vescovi, 2014), this decrease was not observed in the current study with the exception of decreased HSR from 1st to 2nd half in Midfield players. No differences were observed in SPR distance. Previous investigations of adolescent (Vescovi, 2014) and adult female (Hewitt et al., 2014) match-play showed that reductions in TOTAL distance from 1st to 2nd half across all playing positions were the result of decreased HSR and

SPR and increased lower-speed distances. Although TOTAL distance similarly decreased across all playing positions in the current study, the data show this is a result of decreased LOW distances into the 2nd half, along with a small decrease in HSR distance for Midfield players. Somewhat similar results were shown in one investigation in men's soccer, with decreases in TOTAL distance and HSA distances between match halves, but no differences in SPR distance (ES = 0.1) (Bradley & Noakes, 2013). An investigation in match-play in U13 youth female soccer observed similar decreases in TOTAL distance from 1st to 2nd half, but also found non-significant decreases in running distances >13 $km \cdot hr^{-1}$ (3.6 $m \cdot s^{-1}$).

One possible explanation for this finding is a pacing strategy that reduces low-speed movement in order to maintain the ability to perform at high speeds and avoid fatigue (Drust et al., 2007; Edwards & Noakes, 2009; Link & Weber, 2017; Trewin et al., 2018b), though this has been suggested for adverse match conditions such as dehydration and high ambient temperatures. A further explanation from the current data lies in the decreases in AVG speed across all playing positions: decreases in LOW distances would raise AVG speed in the 2nd half due to higher proportions of HSA distance, however the proportions of distances in each speed zone are the same from 1st to 2nd half. This suggests that players spend more time at a standstill during the 2nd half which explains the observed decrease in AVG speed and could be attributed to a pacing strategy to mitigate fatigue and preserve player ability to perform high-speed activity. This fatigue-mitigating strategy has been observed in men's professional soccer, where players were observed to have 14% slower average speed, 9% less walking, and 12.4% less jogging in the 2nd half of matches due to increased time spent stationary (Burgess et al., 2006). This is further supported in the current data by significant decreases in average HR from 1st to 2nd half in all playing positions in FULL match observations.

Increased time at standstill would temporarily decrease HR resulting in a lower average HR across the match half.

Of note are the large CVs observed for SPR distance and SSE counts (26.2 – 60.7%). Although adolescent players are capable of reaching the sprint-speed thresholds, including over soccer-specific sprint distances (Chapter 4), sprint speeds are reached few times in matches on average, as shown in low SSE counts and high variability between match halves. Match-to-match variability in sprinting could account for observed low SSE counts and SPR distances, with large variability for SSE (mean CV = 53%) noted in international women's soccer (Trewin et al., 2018a). Average SSE counts in international women's soccer (14 – 26 in 90 minute matches) (Trewin et al., 2018) are similar to SSE counts in the current study (8 – 13 in 80 minute matches), though in considering the ranges of SSE (1 – 28 in 80 minute matches) in the current study, it appears some players utilise high-speed movement more than others even within playing positions. This potentially reflects higher physical capacity in some players along with greater match experience, as noted outliers at the high end of observed ranges tended to be players with international experience, which aligns with performance differences between international and domestic players as distinguished by HSA (Andersson et al., 2010; Mohr et al., 2008).

In all playing positions, a significant small decrease in DECEL efforts (d = 0.11 – 0.28) was observed from 1st to 2nd half. For Midfield and Defender players, ACCEL efforts showed similar significant reductions from 1st to 2nd half (d = 0.27 – 0.31), but non-significant reductions for Forward players. Investigations of ACCEL and DECEL in professional women's soccer using a higher threshold (±2.0 $m \cdot s^{-2}$) found reductions from 1st to 2nd half regardless of the start or end velocity of the effort (Mara et al., 2017b). In men’s professional soccer, reductions in ACCEL and DECEL using the similar thresholds (±0.5 – 1.0 $m \cdot s^{-2}$) as the current study also observed reductions from 1st to 2nd half (Akenhead et al., 2013; Newans et al., 2019; Russell et al., 2016). With a lack of significant differences between match halves in HSA speed zones, ACCEL and DECEL counts as measures of high-intensity load often performed at low speeds appear to provide a more reliable indication of reductions in high-intensity movement across a match. Acceleration and deceleration have been shown to have greater energy costs than constant running costs (di Prampero, 2005; Osgnach et al., 2010) and have been linked to decreased neuromuscular performance (Nedelec et al., 2014). The observation of frequent accelerations and decelerations (3.3 – 4.5 efforts per minute) in the current study may indicate a high metabolic cost of match-play in adolescent female soccer. The observed decreases in DECEL in all positions and decreases in ACCEL for Midfield and Defender players in FULL between match halves suggest that reductions in ACCEL and DECEL may indicate the onset of fatigue (Mara et al., 2017b).

Further, it has been suggested that repeated decelerations contribute to fatigue due to eccentric loading (Lakomy & Haydon, 2004). Deceleration is often performed prior to a cutting manoeuvre (Hewit et al., 2011), a movement often observed prior to noncontact injury, including ACL injury (Alentorn-Geli et al., 2009). Eccentric movements during deceleration are primarily performed by the quadriceps and gastrocnemius (Andrews et al., 1977). These two findings suggest that repeated deceleration in match-play may have a quadriceps-fatiguing effect that could increase noncontact injury risk in addition to affecting sprint performance. The frequent deceleration requirements of match-play should be of increased interest in adolescent female soccer due to the high risk of noncontact and ACL injury (Hewett et al., 2006) and the potential fatiguing effects of match-play.

Overall, similar decrements in match performance were observed across playing positions in both speed-based and acceleration-based variables, along with reductions in internal match loads. One exception is observed reductions of HSR distance in Midfield players between halves that were not present in Forward and Defender players. These reductions in performance likely reflect a decrease in glycogen stores in the musculature as previous studies have found pronounced muscle glycogen depletion in females in later match stages (Bendiksen et al., 2012; Krustrup et al., 2010). Sprint-speed movement was observed to be highly variable between match halves, potentially reflecting player physical capacity as well as external match factors. Although HSA distances have been shown to decrease between halves in other investigations in women's soccer, this was not observed in the current study which is likely due to a pacing strategy used to preserve high-speed activity, potentially indicative of fatigue onset in the 2nd half. Decreases in acceleration and deceleration efforts may also provide a more sensitive indication of fatigue onset in performance parameters compared to speed-based measures. Importantly, frequent decelerations may increase noncontact injury risk through repeated eccentric loading. The tracking of these match load parameters, where possible, may help coaches and support staff recognise the onset of acute fatigue within match-play.

5.6 Section A – Summary

This section of the current study presents new data on the match loads of adolescent female soccer players in full-match conditions. Positional differences generally observed in women's soccer were also observed in the present study, with Midfield players completing more total distances and Forward players completing more sprint-speed distances. These findings have direct impact on the development of training for adolescent female soccer players with consideration to positional differences in match loads and decreases in performance from 1st to 2nd half. Accelerations and decelerations performed at sub-sprint speeds should also be considered in training in light of the number of accelerations and decelerations observed in match-play relative to low amounts of high-speed movement, which may have a fatiguing effect.

Reductions in FULL match loads from the 1st to 2nd half were observed in the present study, although contrary to previous investigations, reductions were due to increased time at standstill which preserved high-speed performance. Acceleration and deceleration efforts may instead provide a more sensitive indication of fatigue onset as reductions in these measures were noted from 1st to 2nd half and merit further study. Indications of fatigue are present in full-match observations, with reductions in performance over the course of match-play. These findings can assist in the future monitoring of fatigue during match-play within full-match conditions.

CHAPTER 5 – Section B

Analysis of match load in substitute match conditions with comparison to full-match conditions

5.7 Section B – Methods

Substitution rules result in a large variation of observed match loads due to differences in time played (Gentles et al., 2018). In one example in the current study, observed time played for one participant was 73 minutes, however the participant had been substituted off the pitch for 10 minutes during the 2nd half and returned after an injury time, resulting in additional active match-play. In consideration of this, match files were designated as substitute (SUB) if a participant completed <75 minutes in a match, with participants completing ≥75 minutes in a match without a return to match-play designated as full-match. For match files with three sections of time on pitch (n = 8) due to substitution off and return to the pitch within the 2nd half, the two 2nd half sections were considered together for the purpose of evaluating total SUB match loads. The number of match observations in SUB analyses varies due to different substitution strategies utilised.

As in Chapter 5 – Section A, occurrences of poor signal from the HR monitors affecting the calculation of average HR were noted in some match observations. Average HR in match files that were affected were not used for the purposes of this study, resulting in a reduced number of match observations for this variable. For purposes of clarity, average HR was considered separately from the other match variables. Tables 5.8 and 5.9 provides a summary of analyses, number of participants, and number of match files for SUB conditions, comparison of FULL and SUB conditions, and between-half comparison analyses within SUB conditions. In all results tables, the number of match files for each condition are given.

5.7.1 Evaluating match load in substitute conditions

To evaluate substitute match loads in adolescent female soccer players, total match load was compared between the three position categories for SUB match observations using relative data. Relative data were calculated from raw GPS variables averaged over individual time played (variable per minute). To examine the proportion of match load in HSA and low-speed zones, the percentage of TOTAL distance completed in the SPR and HSR speed zones (%SPR and %HSR) and LOW speed zone (%LOW) and the percentage of HIA that were repeat HIA (%REPEAT) were compared between positions within SUB.

To evaluate performance differences between match halves and the effect of extended rest periods on substitute match loads, several analyses were undertaken. (1) Relative data were compared within-participant between 1st and 2nd half for SUB match observations where participants took part in both match halves for ≥5 min per half (n = 72); time played in qualifying match observations was ≥10 min per half. (2) The effect of additional rest, due to a participant being substituted off and later returned to play (SUBrest, n = 38), on differences between 1st and 2nd half match load was also examined. SUBrest included substitutions with an extended rest period including half time and/or a substitution and return to match-play within the 2nd half. No Rest match observations (n = 34) did not have a substitution off during time played and the only rest period was the normal 10-minute half time; participants in the No Rest condition started or were substituted onto the pitch during the 1st half. (3) Average HR as a measure of internal load was compared between 1st and 2nd half periods for SUB conditions. Only substitutes who participated in both halves of a match were included in the analysis of average HR.

5.7.2 Differences between full-match and substitute match loads with reference to playing position

FULL and SUB match loads were compared in several ways. (1) It was hypothesised that a decrease in match load would be observed from 1st to 2nd half in FULL conditions but not in SUB conditions. To test this hypothesis with regards to SUB conditions, FULL and SUB conditions were compared per playing position using relative data. (2) The proportion of match load in HSA and low-speed zones, the percentage of TOTAL distance completed in the SPR and HSR speed zones (%SPR and %HSR) and LOW speed zone (%LOW) and the percentage of HIA that were repeat HIA (%REPEAT) were also compared between FULL and SUB within playing position. Although WR is a relative measure of TOTAL distance, it is a commonly used measure in team sports to evaluate match loads and so is included in raw data results.

5.7.3 Statistical analysis

Statistical analysis was conducted using Excel (Microsoft, Redmond, WA) and SPSS (Version 24, SPSS Inc., Chicago, IL). Data are presented as mean ± standard deviation (SD). All data were assessed for normality using skewness and kurtosis; values for asymmetry and kurtosis between -2 and +2 are considered acceptable to prove normal distribution (George & Mallery, 2010). Levene's test was used to assess the assumption of equal variance for each variable. Where reported, Cohen's *d* for effect size was considered small, moderate, large, very large, and extremely large with values greater than 0.1, 0.3, 0.5, 0.7, and 0.9, respectively (William G Hopkins et al., 2009). Effect sizes for ANOVAs are reported as partial eta squared (η^2) and interpreted as small ($0.01 \leq \eta^2 < 0.06$), moderate ($0.06 \leq \eta^2 < 0.14$), or large ($\eta^2 \geq 0.14$) (Cohen, 1988).

5.7.3.1 Statistical analysis evaluating match loads in substitute conditions

A one-way ANOVA was used to analyse between-position differences in SUB conditions using relative data for SUB. Percentage of total distance for %SPR, %HSR, and %LOW and percentage of HIA for %REPEAT were calculated and a one-way ANOVA was performed to analyse between-position differences for percentage variables. Post hoc analysis was performed with Bonferroni adjustment if equal variances were assumed and Dunnett T3 adjustment if equal variances were not assumed. In the event of a possible violation of assumption of normality, data were re-analysed using the nonparametric equivalent of the test which did not change results.

To compare within-participant differences between the 1st and 2nd halves, paired t-tests were used to compare 1st and 2nd half match variables for SUBrest and No Rest conditions, respectively. A mixed-methods repeated measures ANOVA was performed to assess 1st and 2nd half differences for SUB match observations, using the resting condition (SUBrest or No Rest) as a between-participant factor. Paired t-tests were also used to compare 1st and 2nd half average HR for SUB match observations. In the event of a possible violation of assumption of normality, the nonparametric equivalent of the test was used which did not change results. Coefficient of variation (CV) as a percentage was calculated as CV = (SD/mean)*100. Statistical significance was accepted at $p < 0.05$.

5.7.3.2 Statistical analysis evaluating differences between FULL and SUB match loads

Independent t-tests assessed the differences between FULL and SUB conditions using relative data for both conditions. Independent t-tests were also used to assess differences between FULL and SUB conditions for percentage of total distance for %SPR, %HSR, and %LOW and percentage of HIA for %REPEAT.

Table 5.8 Summary of analyses, number of participants, and number of match files for evaluating match loads in substitute conditions and comparison of FULL and SUB match loads

	SUB total match load			FULL v SUB total match load		
Comparison	Between positions			Between conditions		
Data	Relative			Relative		
Position	F	M	D	F	M	D
# of players	10	19	11	18	32	26
# of match observations	23	51	30	42	80	74

Table 5.9 Summary of analyses, number of participants, and number of match files for evaluating differences in 1st and 2nd half match loads in substitute conditions

	SUB 1st v 2nd half external match load; effect of Rest on substitutes			SUB 1st v 2nd half internal match load		
Comparison	Within-participant			Within-participant		
Data	Relative			Heart rate		
Position	F	M	D	F	M	D
# of players	9	16	11	7	14	9
# of match observations	13	39	20	9	25	11

5.8 Section B – Results

5.8.1 Evaluating match loads in substitute conditions

Raw data for all GPS variables for SUB match load are shown in Table 5.10. Between-position comparisons for SUB are also in Table 5.10 along with the relative means for each variable used in the between-position comparisons. In Midfield match observations, higher WR and more relative distance completed in the LOW speed zone were noted compared to Forward and Defender match observations, with moderate effect sizes (partial $\eta^2 = 0.089$ – 0.139) for both variables between positions. Large effect sizes (partial $\eta^2 = 0.143$) were noted for differences in relative distance completed above the sprint-speed threshold, with significantly more relative sprint distance completed in Forward match observations than in Midfield and Defender match observations. Relative SSE counts were significantly higher in Forward match observations than Midfield with a large effect size (partial $\eta^2 = 0.146$) between positions. Higher relative ACCEL and DECEL counts were noted in Midfield match observations compared to Forward only, with moderate (partial $\eta^2 = 0.106$) and large (partial $\eta^2 = 0.149$) effect sizes observed between positions, respectively.

Between-position comparisons of percentage variables for LOW, HSR, and SPR distances and REPEAT are shown in Figure 5.3. SUB Forward match observations had higher percent SPR distances compared to Midfield and Defender SUB conditions with extremely large ($d > 0.9$) effect size. No other significant between-position differences for percentage variables were observed within SUB conditions.

5.8.2 Evaluating differences between FULL and SUB conditions

Comparison of FULL and SUB conditions per playing position using relative data for all variables is shown in Table 5.11. Although variables such as WR and relative distances over

SPR threshold, HSR threshold, and in the LOW speed zone show higher means for substitutes compared to full-match Forward match observations, these differences were not significant. No significant differences between FULL and SUB conditions were observed for any external match load variables for Forward match observations. Midfield SUB had higher WR, relative HSR distances, relative ACCEL, and relative DECEL compared to full-match match observations, with large (*d* = 0.59), large (*d* = 0.63), very large (*d* = 0.88), and extremely large (*d* = 0.92) effect sizes noted, respectively. For Defender match observations, substitutes also had higher WR, relative HSR distances, relative ACCEL, and relative DECEL compared to full-match participants, with very large (*d* = 0.84), large (*d* = 0.58), extremely large (*d* = 1.00), and large (*d* = 0.67) effect sizes, respectively. Additionally, Defender substitutes completed more relative LOW distances, HIA efforts, and REPEAT efforts compared to full-match participants, with very large (*d* = 0.71), very large (*d* = 0.78), and moderate (*d* = 0.50) effect sizes, respectively.

In comparing FULL and SUB percentage variables for LOW, HSR, and SPR distances and REPEAT as shown in Figure 5.3, two differences were observed between FULL and SUB conditions: (1) a significant difference was observed between conditions for Midfield match observations for percent HSR distance (large effect size, $d > 0.5$) with substitutes having a higher percent HSR; (2) a significant difference was also observed between FULL and SUB for Defender match observations, with percent REPEAT efforts higher for substitutes (large effect size, $d > 0.5$). Forward match observations in both FULL and SUB conditions had higher percent SPR distances compared to Midfield and Defender.

Table 5.10 Raw and relative data for SUB match observations per playing position for all variables and one-way ANOVA results comparing playing position for each match variable using relative data. Relative data for WR is not reported as WR is a relative variable of TOTAL.

					Position Main Effect		Pairwise Comparison
		Forward	**Midfield**	**Defender**	F	(p-value)	(p-value)
		n = 23	n = 51	n = 30		partial η2	Cohen's *d*
Time played	Mean ± SD	51 ± 13	53 ± 13	51 ± 17	0.35	(p = 0.709) NS	
TOTAL (m)	Mean ± SD	5210.4 ± 1406.2	5848.3 ± 1546.4	5254.3 ± 1900.6			
WR (m·min^{-1})	Mean ± SD	103.0 ± 11.9	109.6 ± 8.9	103.6 ± 11.1	4.93	(p = 0.009) η^2 = 0.089	M > F & D (p = 0.035 & p = 0.035) *d* = 0.63 & 0.60
SPR (m)	Mean ± SD	177.1 ± 94.5	99.1 ± 100.1	110.3 ± 78.4	8.43	(p <0.001) η^2 = 0.143	F > M & D (p <0.001 & p = 0.021) *d* = 0.80 & 0.77
	relSPR Mean ± SD	3.4 ± 1.5	1.8 ± 1.7	2.2 ± 1.4			
HSR (m)	Mean ± SD	435.9 ± 218.4	467.0 ± 245.4	401.3 ± 208.5	0.42	(p = 0.66) NS	
	relHSR Mean ± SD	8.3 ± 3.3	8.6 ± 3.6	7.9 ± 3.0			
LOW (m)	Mean ± SD	4597.3 ± 1161.1	5282.2 ± 1362.5	4742.7 ± 1718.8	8.13	(p = 0.001) η^2 = 0.139	M > F & D (p <0.001 & p = 0.014) *d* = 0.54 & 0.35
	relLOW Mean ± SD	91.1 ± 9.5	99.2 ± 7.9	93.3 ± 10.0			

SSE	Mean ± SD	11 ± 6	6 ± 6	7 ± 5	8.60	(p <0.001)	F > M
	relSSE Mean ± SD	0.2 ± 0.1	0.1 ± 0.1	0.2 ± 0.1		$\eta^2 = 0.146$	(p <0.001)
							d = 0.83
HIA	Mean ± SD	53 ± 26	59 ± 29	49 ± 20	0.71	(p = 0.496)	
	relHIA Mean ± SD	1.0 ± 0.4	1.1 ± 0.4	1.0 ± 0.3		NS	
REPEAT	Mean ± SD	23 ± 17	26 ± 19	20 ± 11	0.40	(p = 0.672)	
	relREPEAT Mean ± SD	0.4 ± 0.3	0.5 ± 0.3	0.4 ± 0.2		NS	
ACCEL	Mean ± SD	185 ± 69	235 ± 77	204 ± 81	5.96	(p = 0.004)	M > F
	relACCEL Mean ± SD	3.6 ± 0.9	4.4 ± 0.8	4.1 ± 0.8		$\eta^2 = 0.106$	(p = 0.003)
							d = 0.68
DECEL	Mean ± SD	177 ± 73	243 ± 80	204 ± 84	8.84	(p <0.001)	M > F
	relDECEL Mean ± SD	3.5 ± 1.1	4.5 ± 0.9	4.1 ± 1.1		$\eta^2 = 0.149$	(p <0.001)
							d = 0.86

Time played = active match-play time for 1st and 2nd half (min); TOTAL = total distance (m); WR = work rate ($m \cdot min^{-1}$); relSPR = sprinting distance per minute played; relHSR = high-speed running distance per minute played; relLOW = low-speed running distance per minute played; relSSE = number of sprint-speed running efforts per minute played; relHIA = number of high-intensity acceleration efforts per minute played; relREPEAT = number of repeat HIA efforts per minute played; relACCEL = number of accelerations per minute played; relDECEL = number of decelerations per minute played. Partial η2 – partial eta squared for effect size. NS – p-value not significant. F – Forward, M – Midfield, D – Defender. P-value is significant at $p < 0.05$.

Table 5.11 Relative data (mean ± SD) and comparison for FULL and SUB total match loads per playing position

	Forward			**Midfield**			**Defender**		
	FULL n = 19	**SUB** n = 23	Cohen's d	**FULL** n = 29	**SUB** n = 51	Cohen's d	**FULL** n = 44	**SUB** n = 30	Cohen's d
Time played	80 ± 0	51 ± 13		80 ± 1	53 ± 13		80 ± 1	51 ± 17	
WR	97.5 ± 11.7	103.0 ± 11.9		105.1 ± 6.1	109.6 ± 8.9*	0.59	95.2 ± 8.8	103.6 ± 11.1*	0.84
relSPR	2.7 ± 1.1	3.4 ± 1.5		1.5 ± 1.5	1.8 ± 1.7		1.9 ± 1.1	2.2 ± 1.4	
relHSR	8.0 ± 3.1	8.3 ± 3.3		6.5 ± 3.1	8.6 ± 3.6*	0.63	6.3 ± 2.5	7.9 ± 3.0*	0.58
relLOW	86.7 ± 8.7	91.1 ± 9.5		97.1 ± 7.8	99.2 ± 7.9		87.0 ± 7.7	93.3 ± 10.0*	0.71
relSSE	0.2 ± 0.1	0.2 ± 0.1		0.1 ± 0.1	0.1 ± 0.1		0.1 ± 0.1	0.2 ± 0.1	
relHIA	1.1 ± 0.4	1.0 ± 0.4		0.9 ± 0.3	1.1 ± 0.4		0.8 ± 0.2	1.0 ± 0.3*	0.78
relREPEAT	0.5 ± 0.3	0.4 ± 0.3		0.4 ± 0.2	0.5 ± 0.3		0.3 ± 0.2	0.4 ± 0.2*	0.50
relACCEL	3.6 ± 1.2	3.6 ± 0.9		3.5 ± 1.2	4.4 ± 0.8*	0.88	3.3 ± 0.8	4.1 ± 0.8*	1.00
relDECEL	3.3 ± 1.4	3.5 ± 1.1		3.3 ± 1.6	4.5 ± 0.9*	0.92	3.4 ± 1.0	4.1 ± 1.1*	0.67

Time played = active match-play time for 1st and 2nd half combined (min); WR = work rate ($m \cdot min^{-1}$); relSPR = sprinting distance per minute played; relHSR = high-speed running distance per minute played; relLOW = low-speed running distance per minute played; relSSE = number of sprint-speed running efforts per minute played; relHIA = number of high-intensity acceleration efforts per minute played; relREPEAT = number of repeat HIA efforts per minute played; relACCEL = number of accelerations per minute played; relDECEL = number of decelerations per minute played. *denotes significant difference between FULL and SUB conditions, $p < 0.05$.

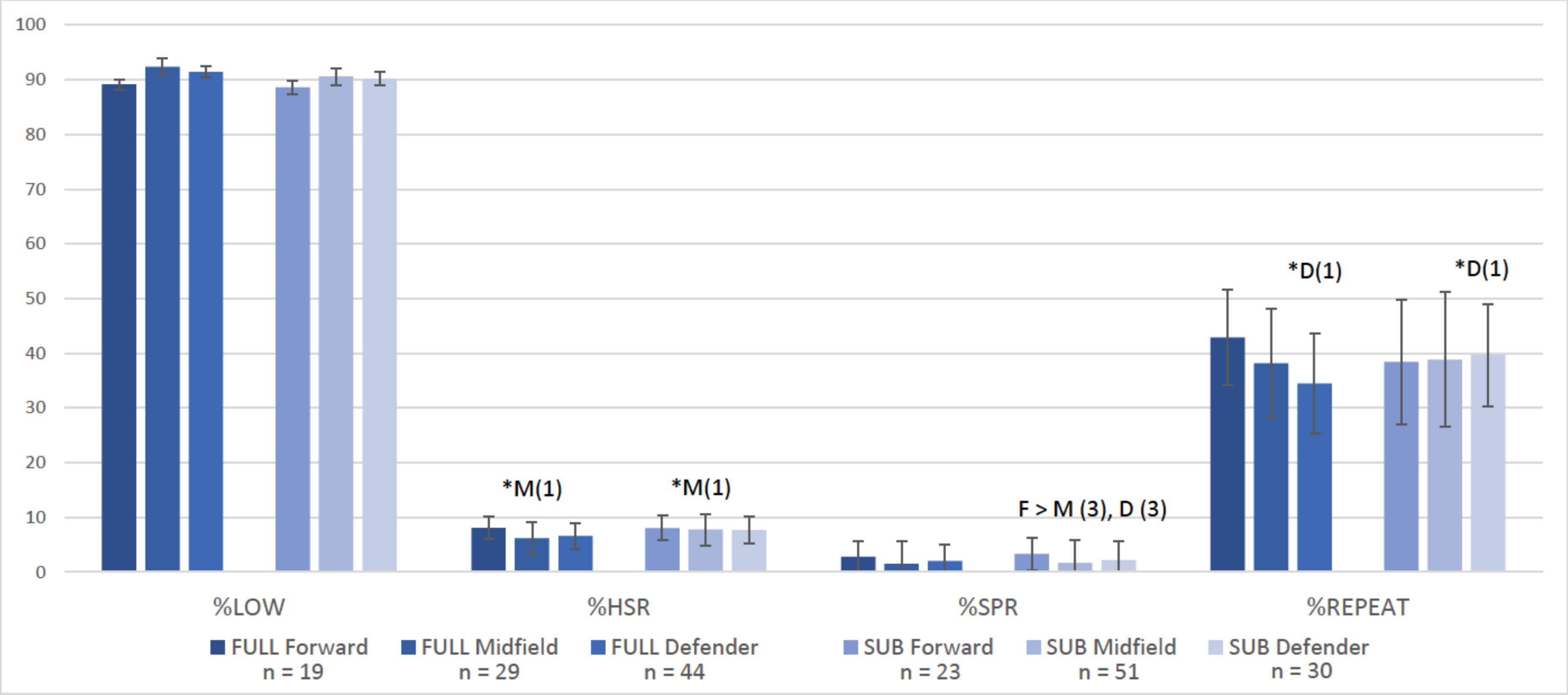


Figure 5.3 Percentage variables for LOW, HSR, and SPR distance and percentage of repeated HIA (mean ± SD) with effect sizes for between-position within SUB conditions and between-condition (FULL v SUB) differences, from match observations as in Tables 5.5 and 5.10. %LOW = percentage of total distance completed in LOW speed zone; %HSR = percentage of total distance completed in HSR speed zone; %SPR = percentage of total distance completed in SPR speed zone; %REPEAT = percentage of HIA efforts that are repeat efforts. Numbers denote effect size: 1 = large (>0.5), 2 = very large (>0.7), and 3 = extremely large (>0.9); * = significant difference between FULL v SUB, p <0.05; < denotes significant difference between positions, p <0.05; F = Forward, M = Midfield, D = Defender.

5.8.3 Differences in 1st and 2nd half SUB match loads

Relative data for 1st and 2nd half match loads for SUB conditions per playing position are shown in Table 5.12, along with separate relative data for SUBrest and No Rest conditions. Extended rest periods for SUBrest match observations were 30 ± 6 minutes including the 10-minute half time; within-2nd half rest periods (n = 8) were 12 ± 4 minutes. No significant interactions were observed between SUBrest and No Rest conditions except for Defender match observations with relative SPR distance ($p = 0.035$, partial $\eta 2 = 0.224$) and relative SSE efforts ($p = 0.003$, partial $\eta 2 = 0.390$), both with large effect sizes. Increases in relative SPR and relative SSE from 1st to 2nd half in the No Rest condition were observed with decreases in the SUBrest condition, however paired t-tests only revealed a significant difference between 1st and 2nd half for relative SSE efforts for No Rest with an extremely large effect size ($d = 1.0$). No other significant differences in either rest or combined SUB conditions for Defender match observations between 1st and 2nd half were observed.

A significant difference was observed between 1st and 2nd half in the No Rest condition for relative HSR distance in Forward match observations, with an extremely large effect size ($d = 1.0$). Average speed significantly decreased from 1st to 2nd half in No Rest and combined SUB conditions with a moderate effect size ($d = 0.50$) for both findings. No other significant differences were shown for SUB conditions in Forward match observations.

In Midfield match observations for SUB conditions, paired t-tests revealed a significant difference in WR between match halves with decreased work rate from 1st to 2nd half in No Rest, SUBrest, and combined SUB conditions with large reported effect sizes ($d = 0.57 – 0.60$). Similar significant differences were noted for relative LOW distance with decreases from 1st to 2nd half, with very large effect sizes ($d = 0.75 – 0.85$). A significant decrease from 1st to 2nd half was noted in relative HIA efforts for No Rest with a moderate effect size (*d* = 0.40), but no differences were revealed for SUBrest or combined SUB conditions. Average speed significantly decreased from 1st to 2nd half in No Rest, SUBrest, and combined SUB conditions, with moderate to extremely large effect sizes (*d* = 0.50 – 1.0). A decrease from 1st to 2nd half was shown for No Rest, SUBrest, and combined SUB conditions for relative ACCEL count, though only No Rest and combined SUB conditions were significantly different, both with moderate effect sizes (*d* = 0.40 – 0.43). Similar decreases in No Rest, SUBrest, and combined SUB conditions in Midfield were shown for relative DECEL count, and similarly only No Rest and combined SUB conditions were significantly different, with large (*d* = 0.61) and moderate (*d* = 0.40) effect sizes, respectively.

Average heart rate for SUB match observations for 1st and 2nd match halves are shown in Table 5.13. Paired t-tests did not reveal any significant differences within SUB match observations between halves. Low mean CVs (<5%) were noted for between 1st and 2nd half. Percent of estimated maximal heart rates ranged from 86 – 93%, with Defender match observations in SUB showing lower percentages compared to Forward and Defender match observations.

Table 5.12 Relative data (mean ± SD) for 1st and 2nd half match loads per position for SUB match observations with comparison for No Rest and SUBrest

		Forward				**Midfield**				**Defender**			
		No Rest = 7, SUBrest = 6				No Rest = 15, SUBrest = 24				No Rest = 12, SUBrest = 8			
		1st half	2nd half	p-value	Cohen's *d*	1st half	2nd half	p-value	Cohen's *d*	1st half	2nd half	p-value	Cohen's *d*
Time played	No Rest	34 ± 10	27 ± 9			27 ± 13	29 ± 10			40 ± 0	23 ± 6		
	SUBrest	38 ± 6	22 ± 9			30 ± 9	30 ± 10			35 ± 10	23 ± 8		
	ALL	36 ± 8	25 ± 9			29 ± 11	29 ± 10			38 ± 7	23 ± 7		
WR	No Rest	101.6 ± 9.0	94.3 ± 10.9			115.5 ± 14.5	107.4 ± 12.4	0.010	0.60	104.9 ± 12.5	102.6 ± 13.6		
	SUBrest	109.4 ± 15.7	104.6 ± 21.3			113.4 ± 7.3	109.2 ± 6.7	0.017	0.60	104.9 ± 11.8	109.5 ± 11.7		
	ALL	105.2 ± 12.6	99.1 ± 16.7			114.2 ± 10.6	108.5 ± 9.2	<0.001	0.57	104.9 ± 11.9	105.4 ± 13.0		
relSPR^{SDef}	No Rest	3.4 ± 1.7	3.7 ± 2.2			1.4 ± 1.7	1.9 ± 1.8			1.6 ± 1.0	2.6 ± 1.9		
	SUBrest	3.9 ± 1.8	3.9 ± 1.9			2.0 ± 2.3	2.5 ± 2.3			2.6 ± 1.3	2.0 ± 2.0		
	ALL	3.7 ± 1.7	3.7 ± 1.9			1.8 ± 2.1	2.3 ± 2.1			2.0 ± 1.2	2.3 ± 1.9		
relHSR	No Rest	9.3 ± 1.8	7.2 ± 2.3	0.019	1.0	9.1 ± 5.1	9.3 ± 3.6			8.4 ± 3.9	7.4 ± 3.4		
	SUBrest	8.8 ± 6.8	8.9 ± 5.6			8.8 ± 4.3	10.0 ± 3.6			6.9 ± 3.1	7.3 ± 3.1		
	ALL	9.1 ± 4.6	8.0 ± 4.1			8.9 ± 4.6	9.7 ± 3.6			7.8 ± 3.6	7.4 ± 3.2		
relLOW	No Rest	88.8 ± 9.4	83.5 ± 8.2			105.0 ± 11.5	96.2 ± 9.2	0.002	0.85	94.8 ± 10.9	92.6 ± 11.2		
	SUBrest	95.9 ± 8.9	91.9 ± 18.7			102.4 ± 7.7	96.7 ± 7.4	0.003	0.75	95 ± 11.5	100.2 ± 8.9		
	ALL	92.1 ± 9.5	87.4 ± 14.1			103.4 ± 9.3	96.5 ± 8.0	<0.001	0.80	94.9 ± 10.8	95.6 ± 10.8		
relSSE^{SDef}	No Rest	0.2 ± 0.1	0.2 ± 0.1			0.1 ± 0.1	0.1 ± 0.1			0.1 ± 0.1	0.2 ± 0.1	0.015	1.0
	SUBrest	0.2 ± 0.1	0.2 ± 0.1			0.1 ± 0.1	0.1 ± 0.1			0.2 ± 0.1	0.1 ± 0.1		
	ALL	0.2 ± 0.1	0.2 ± 0.1			0.1 ± 0.1	0.1 ± 0.1			0.1 ± 0.1	0.2 ± 0.1		
relHIA	No Rest	1.0 ± 0.3	1.0 ± 0.3			1.3 ± 0.5	1.1 ± 0.5	0.019	0.40	0.9 ± 0.2	1.0 ± 0.3		
	SUBrest	1.0 ± 0.5	1.1 ± 0.7			1.1 ± 0.4	1.1 ± 0.4			0.9 ± 0.3	1.0 ± 0.4		
	ALL	1.0 ± 0.4	1.0 ± 0.5			1.2 ± 0.5	1.1 ± 0.4			0.9 ± 0.2	1.0 ± 0.3		
relREPEAT	No Rest	0.4 ± 0.2	0.4 ± 0.2			0.6 ± 0.5	0.5 ± 0.4			0.4 ± 0.1	0.3 ± 0.2		
	SUBrest	0.5 ± 0.4	0.5 ± 0.7			0.5 ± 0.3	0.5 ± 0.3			0.4 ± 0.2	0.4 ± 0.2		
	ALL	0.4 ± 0.3	0.5 ± 0.4			0.5 ± 0.4	0.5 ± 0.3			0.4 ± 0.2	0.4 ± 0.2		

AVG	No Rest	1.6 ± 0.2	1.5 ± 0.2	0.005	0.50	1.8 ± 0.2	1.7 ± 0.2	0.005	0.50	1.7 ± 0.2	1.6 ± 0.2		
	SUBrest	1.6 ± 0.2	1.5 ± 0.2			1.8 ± 0.1	1.7 ± 0.1	0.004	1.0	1.7 ± 0.2	1.6 ± 0.2		
	ALL	1.6 ± 0.2	1.5 ± 0.2	0.025	0.50	1.8 ± 0.1	1.7 ± 0.2	<0.001	0.63	1.7 ± 0.2	1.6 ± 0.2		
relACCEL	No Rest	3.3 ± 0.9	3.0 ± 1.0			4.8 ± 1.2	4.3 ± 1.1	0.002	0.43	4.1 ± 0.9	4.0 ± 0.8		
	SUBrest	4.1 ± 1.0	4.3 ± 1.1			4.5 ± 0.9	4.2 ± 0.8			3.9 ± 1.0	4.0 ± 1.1		
	ALL	3.7 ± 1.0	3.6 ± 1.2			4.6 ± 1.1	4.2 ± 0.9	<0.001	0.40	4.0 ± 0.9	4.0 ± 0.9		
relDECEL	No Rest	3.0 ± 1.2	2.7 ± 1.1			5.1 ± 1.2	4.4 ± 1.1	<0.001	0.61	4.0 ± 1.2	3.9 ± 1.3		
	SUBrest	3.9 ± 0.9	4.2 ± 1.2			4.7 ± 1.0	4.4 ± 0.8			4.2 ± 1.2	3.9 ± 1.4		
	ALL	3.4 ± 1.2	3.4 ± 1.3			4.8 ± 1.1	4.4 ± 0.9	<0.001	0.40	4.0 ± 1.2	3.9 ± 1.3		

No Rest = match observations where participants were not substituted off during time played (10-minute half time only); SUBrest = match observations where participants were substituted off and later returned to match-play; ^{SDef} = significant interaction between half and rest conditions for Defender, p <0.05.

Table 5.13 Average heart rate (bpm) (mean ± SD) for 1st and 2nd half in SUB match observations. 95% CI = 95% confidence interval. Within-participant measures for SUB are not significantly different, p >0.05.

		SUB				
		n	1st half	2nd half	CV	Cohen's *d*
	Time played (min)		31 ± 11	27 ± 10		
Forward	Mean ± SD	9	180 ± 8	177 ± 7	1.9	
	95%CI		174-186	172-182		
	%maxHR		91 ± 4.2	90 ± 3.6		
Midfield	Mean ± SD	25	179 ± 10	177 ± 6	2.5	
	95%CI		175-183	174-179		
	%maxHR		90 ± 5.0	90 ± .1		
Defender	Mean ± SD	11	176 ± 10	171 ± 9	3.3	
	95%CI		169-183	165-176		
	%maxHR		89 ± 4.9	86 ± 4.3		

n = number of match observations; %maxHR = percentage of maximal HR; 95%CI = 95% confidence interval for the mean; CV = mean coefficient of variation as a percentage.

5.8.4 Summary of substitute condition results and comparison of FULL and SUB conditions

For SUB conditions, Midfield players were observed to have higher WR and relLOW distance compared to Forward and Defender players. Forward players were observed to have higher relSPR distances compared to Midfield players and Defenders, and more SSE counts compared to Midfield players. SUB Forward players also had higher proportions of SPR distance compared to other positions. In SUB conditions, Midfield players had higher ACCEL and DECEL counts compared to Forward players. In comparing FULL and SUB conditions within playing position, there were no significant differences between conditions for Forwards. Midfield and Defender SUB had higher relative WR, HSR distance, and ACCEL and DECEL counts. Defender SUB also had higher LOW distances, HIA and repeat HIA counts, as well as higher proportions of HIA efforts that were repeated efforts compared to Defender FULL.

In comparing 1st and 2nd half match loads in SUB conditions with consideration to No Rest and SUBrest conditions, No Rest Forward players showed decreases in HSR distance and combined SUB Forward players observed decreases in AVG speed. Midfield SUB conditions observed decreases in WR, LOW distance, AVG speed, and ACCEL and DECEL counts. No Rest Midfield players also observed a decrease in HIA counts. In No Rest Defender players, a significant increase was observed in SSE counts, with a significant interaction for No Rest and SUBrest conditions for this parameter. In comparing average HR from 1st to 2nd halves, no significant differences were observed in SUB conditions.

5.9 Section B – Discussion

5.9.1 Evaluating match loads in substitute conditions

5.9.1.1 The effect of substitutions on positional differences

This is the first study to report on substitute match loads in adolescent female soccer. In comparing playing positions within substitute match observations, similarities to the positional differences of full-match players were observed (Chapter 5, Section A, 5.4.1 Match loads in full-match conditions). SUB Midfield match observations had higher WR and relative LOW distances compared to SUB Forward and Defender match observations, which similar differences were observed in FULL match observations. SUB Forward match observations completed higher relative SPR distances compared to both SUB Midfield and Defender, the same as positional differences observed in FULL match observations. SUB Forward match observations also showed higher relative SSE compared with Midfield, though not Defender, where FULL Forward match observations for SSE were significantly higher than both Midfield and Defender. Positional differences for SUB were also observed in %SPR, where SUB Forward players had higher proportions of SPR distance than Midfield and Defender, the same as in the FULL condition.

Differences between FULL and SUB conditions within playing position comparisons were also noted. In FULL conditions, all positions had similar ACCEL and DECEL counts, however in SUB conditions, Midfield players had higher ACCEL and DECEL counts compared to Forward players only. Where FULL match observations revealed Forward players had lower proportions of LOW distance compared to Midfield and Defender, SUB match observations were not significantly different between positions. Proportions of HSR and percent REPEAT efforts were also not significantly different between positions in the SUB condition but were significantly different in the FULL condition.

An effect of substitutions on position profiles compared to full-match position profiles is noted within acceleration-based variables for SUB Midfield players completing higher numbers of ACCEL and DECEL, suggesting SUB Midfield players perform more high-intensity movement at lower speeds when entering match-play. A lack of positional differences for proportions of distances in speed zones below the SPR threshold for SUB players suggests similar match load patterns for players entering match-play though this does not affect speed-based position profiles. For substitutes, speed-based movement analysis shows similar position differences for match load compared to full-match players, with SUB Midfield players completing higher relative total distance and SUB Forward players completing more relative sprinting. Although some differences in substitute positional profiles are noted, substitutions generally do not affect playing position profiles. Training development does not require differentiation between substitutions and full-match performance expectations per position.

5.9.1.2 The effect of substitutions on relative match loads

In directly comparing SUB and FULL match loads using relative variables, no significant differences between SUB and FULL were observed for Forward players, though several differences were noted for Midfield and Defenders, particularly higher work rates, higher relative HSR distance, and higher relative ACCEL and DECEL efforts for SUB match observations. SUB Defender match observations additionally had higher relative HIA and REPEAT efforts compared to FULL Defender. Proportions of distance in SPR, HSR, or

LOW speed zones were similar between SUB and FULL conditions except for a higher proportion of relative HSR in SUB Midfield compared to FULL Midfield, and higher percent REPEAT efforts in SUB Defender compared to FULL Defender. Together, the data show that use of substitutions has a significant effect on relative match loads for Midfield and Defender positions, including more high-intensity movement for SUB Defender players. This may reflect an ‘all-out’ strategy in match-play by substitute players upon pitch entry (Waldron & Highton, 2014). In Forward players, the lack of significant differences between SUB and FULL conditions likely reflects the intermittent nature of the position, with a positional focus on sprinting compared to total distance and with the aim to score goals (Faude et al., 2012; Gonçalves et al., 2014).

By comparison, in US college women’s soccer, similar relative match loads across different speed zones per match half were observed for both FULL and SUB conditions for both 1st and 2nd halves, though SUB Defender players had higher proportions of HSA distance in the first half ($\eta^2 = 0.200$) (Vescovi & Favero, 2014); only half-match observations were used to compare substitutes and complete-half players due to low number of complete full-match observations in women’s college soccer. In international women’s soccer, comparing substitutes with full-match players (Trewin et al., 2017) under limited substitution rules, substitutes had higher relative WR and HSA (>4.58 $m \cdot s^{-1}$) distance compared to full-match players, however, the study did not differentiate between substitutes in different playing positions. In a recent review of substitutions in soccer, data for substitute players in men’s soccer was conflicting especially with regards to HSA, though a pattern of increased work rate in substitute players compared to full-match players was noted (Hills et al., 2018). With different substitution patterns utilised by coaches between women’s college soccer (Favero et al., 2015), limited substitutions in men’s soccer and women’s international soccer

(Hills et al., 2018; Trewin et al., 2017), and unlimited substitutions in the current study, it is difficult to draw strong comparisons. Data from the current study suggests there is a unique effect of the use of unlimited substitutions in adolescent female soccer with higher WR, HSR, and ACCEL and DECEL by substitutes over shorter durations of match-play, particular to Midfield and Defender players. Substitutes in Midfield and Defender positions complete higher-intensity movement when entering match-play. This information highlights a potential need to develop training around the higher relative match load of substitutes in adolescent female soccer, balancing with the maintenance of performance over longer match-play periods expected in full-match conditions.

5.9.1.3 The effect of substitutions on indications of internal match load

For indications of internal load, the means and percentages of estimated HR_{max} were similar between SUB and FULL match observations (Tables 5.7 and 5.13). This data reflect findings in international women's soccer players that were observed to have similar heart rates regardless of match competition level, although international competitions had greater external match loads (Andersson et al., 2010). While similar mean average heart rates are noted across FULL and SUB conditions, only FULL conditions were noted to have significant 1st to 2nd half differences in average HR. Defender match observations in both FULL and SUB had lower percentages of max HR compared to Forward and Midfield match observations, suggesting lower internal match loads for Defender players. Percentages of estimated HR_{max} were higher in the current study (86 – 93%) compared to the 86 – 87% HR_{max} observed in other studies in women's soccer (Andersson et al., 2010; Barbero-Álvarez et al., 2008; Krustrup et al., 2005, 2010). This is likely due to the use of an estimation equation for maximal heart rate instead of a direct measurement, which was outside the scope of this study.

5.9.2 Differences in 1st and 2nd half match loads for substitute conditions

5.9.2.1 The effect of substitutions on 1st and 2nd half match loads

This study is the first to report on the effect of unlimited substitutions on match loads in adolescent soccer where substitutes participated in both match halves with or without an extended rest period. Differences between 1st and 2nd halves observed in FULL match conditions (Chapter 5, Section A, 5.4.2 Differences in 1st and 2nd half match loads for full-match conditions) were absent in SUB Forward and SUB Defender. In women's college soccer, proportions of distance in different speed zones did not change in substitutes across playing positions, except for SUB Defender players who were observed to have higher proportions of HSA distances in the 1st half (Vescovi & Favero, 2014). One aim of utilising frequent substitutions in women's college soccer is to mitigate fatigue during match-play (Favero et al., 2015); this aim appears to be realised in college soccer as shown in Vescovi and Favero (2014) and similarly in the current study for Midfield and Defenders. However, reductions from 1st to 2nd half were observed in SUB Midfield for WR, relLOW distances, relACCEL counts, and relDECEL counts, similar to FULL match observations. Additionally, indications of internal load in SUB match observations show no significant differences between 1st and 2nd half average HR for all playing positions. Substitutions appear to have a positive effect on the intensities of match load parameters in Forward and Defender players, mitigating indications of fatigue during match-play and suggesting an absence of a pacing strategy compared to FULL match observations in the current study. However, this does not appear to be the case for external match loads in Midfield players despite high numbers of substitutions for Midfield players across matches in the study.

5.9.2.2 The effect of rest on substitution match loads

Unique to the study is the use of a Rest condition to compare substitutes that were involved in both match halves with a normal rest period for half time (No Rest) to substitutes that had an extended rest period and/or a rest period within the 2nd half (SUBrest). In the current study, reductions between 1st and 2nd half were noted in relHSR for No Rest Forward players, and relHIA, relACCEL, and relDECEL for No Rest Midfield players; significant differences in these variables were not observed in SUBrest conditions. In Midfield players, both No Rest and SUBrest conditions were observed to have significant reductions in WR and relLOW distances. Agreement between No Rest and SUBrest conditions for WR and relLOW in conjunction with similar decrements in these variables from 1st to 2nd half observed in FULL match loads suggest that use of substitutions do not mitigate the phenomenon of reduced speed-based performance in later match stages for Midfield players. In women's college soccer, SUB Midfield and Defender players that were substituted out of the match and later returned to match-play were shown to maintain performance, though SUB Forward players showed lower activity level when returning to match-play (Vescovi & Favero, 2014), which aligns with the previous finding in the current study of no significant differences in relative variables between SUB and FULL Forward match observations. Although decrements in WR and LOW distance are noted in both No Rest and SUBrest Forward players in the current study, these differences were non-significant.

Overall, the use of substitutions appears to mitigate performance reductions between halves in Forward and Defender players except for a large reduction in relHSR for No Rest Defender players as well as decreases in AVG speed; these parallel reductions appear to be related and could point to a fatigue effect in No Rest substitute players. In some cases, non-significant increases in performance between 1st and 2nd half are observed in different playing positions, such as increases in relHSR across all SUBrest playing positions. Non-significant increases in relSPR for combined SUB Midfield and Defenders were also observed, however relSPR distances were highly varied with no SPR distances observed in some individual SUB match observations, similar to varied or low SPR distances observed in FULL conditions. In total, substitutions and particularly substitutions with an extended or additional rest period allow for recovery within a match to maintain performance upon re-entry to match-play. These findings have implications for use of unlimited substitutions in adolescent female soccer to maintain team performance across match-play and to mitigate indications of fatigue onset in later match stages. However, the lack of full-match playing experience for some players might not provide the necessary physical demands for adaptation and preparation for higher levels of play, as observed in talented NCAA women's players who struggle at international camps due to frequent use of substitutions in college soccer (Favero et al., 2015). Substitution use may benefit players in mitigating fatigue onset during match-play thereby reducing fatigue-contributed injury risk (de Noronha et al., 2019; Griffin et al., 2006; Navarro Cabello et al., 2015), however this should be balanced with player development.

5.10 Section B – Summary

This section of the study presents new data on the substitute match loads of adolescent female soccer players. Positional differences generally observed in women's soccer and in

Section A in full-match observations in the current study were also observed in substitute match observations, with Midfield players completing more total distances and Forward players completing more sprint-speed distances. Substitutes in Midfield and Defender positions were observed to have higher-intensity work rates compared to full-match players; differences between relative match loads of substitutes and full-match players were not seen in Forward players. These findings have direct impact on the development of training for adolescent female soccer players especially in relation to higher-intensity physical load over shorter match-play periods by substitutes, and accelerations and decelerations performed at sub-sprint speeds relative to low amounts of high-intensity movement observed in match-play.

While reductions in FULL match loads from the 1st to 2nd half were observed (Chapter 5, Section A, 5.4.2 Differences in 1st and 2nd half match loads for full-match conditions), the use of substitutions appears to mitigate observed reductions between match halves for Forward and Defender players, though this mitigation was not seen in speed-based variables for substitute Midfield players. Overall, use of substitutions and extended rest periods mitigates reductions in match performance and could allow for increased performance upon return to match-play, however this should be balanced with player development as players advance into longer matches or encounter match-play with limited substitutions. Indications of fatigue are present in full-match observations and substitute Midfield match observations with reductions in performance over the course of match-play. These findings could be important to future monitoring of fatigue during match-play.

5.11 Study Limitations

Some limitations are noted in the current study. GPS tracks movement by measuring displacement and as such has inherent limitations in that is does not differentiate if a player's movement includes backwards running or jumping which increase the energy cost of match-play (Drust et al., 2007) and are not taken into account in GPS match load measures. A large variety of substitution patterns were utilised by both teams that participated in the current study, and these could not all be taken into account, though the two conditions that might have a large effect on relative match loads (SUBrest and No Rest conditions) were examined. Match-to-match variability as well as other match factors such as final match score and match importance are also not accounted for and require further study in adolescent female soccer.

5.12 Chapter Summary

This study presents new data on the match loads of adolescent female soccer players in full-match and substitute conditions and, to the author's knowledge, is the first study to report on match loads of substitute players in female youth soccer. General positional differences observed in women's soccer were observed in the current study in both full-match and substitute observations, with Midfield players completing more total distances and Forward players completing more sprint-speed distances. While differences between relative match loads of substitutes and full-match players were not seen in Forward players, substitutes in Midfield and Defender positions were observed to have higher-intensity work rates compared to full-match players. These distinctions between positions and between full-match and substitute conditions can inform training regimes for appropriate preparation for position-specific performance.

The study also presents data comparing 1st to 2nd half changes in both full-match and substitute conditions and the effect of substitutions on indications of fatigue onset and performance. Reductions in match loads from 1st to 2nd half were observed in full-match conditions due to increased time at standstill, as part of a pacing strategy to preserve high-speed performance. Although high-speed activity performance was maintained, accelerations and decelerations were reduced from 1st to 2nd half which may provide a more sensitive indication of fatigue onset within match-play. In substitute conditions, 1st to 2nd half reductions were absent for Forward and Defender players suggesting use of substitutions mitigates performance decrements and fatiguing effects, but not for substitute Midfield players despite frequent substitutions in Midfield. These findings can benefit future monitoring of fatigue during match-play, particularly with Midfield players. While use of substitutions may mitigate performance reductions, this should be balanced with player development with the aim to perform across entire matches.

CHAPTER 6

Neuromuscular Response to Match Loads in Adolescent Female Soccer Players

6.1 Introduction

The assessment of sports performance through motion analysis as conducted in Chapter 5 constitutes one method of evaluating neuromuscular response in athletes according to the neuromuscular fatigue (NMF) assessment paradigm (Chapter 2, Section 2.4.3.2) (Knicker et al., 2011). In Chapter 5, players completing full matches demonstrated decreased total distance, low-speed distance (LOW), average speed (AVG), and decelerations (DECEL) across all positions, as well as decreased accelerations (ACCEL) for Midfield and Defender players into the 2nd half, which indicate an onset of fatigue during match-play. Further, decreases in match load as observed in Chapter 5 were not observed in Forward or Defender substitutes, but were observed in Midfield substitute players, demonstrating that the use of substitutions had a potential mitigating effect on indications of fatigue within match-play although this might be position specific.

As discussed in Chapter 5, studies in male professional soccer observed that decreases in match load similar to those observed in female soccer occurred regardless of the score differential (Mohr et al., 2003) and that match performance was not affected by match importance (Bradley & Noakes, 2013). These findings suggest neuromuscular fatigue (NMF) is a factor in the observed reduction of match load as opposed to player-controlled reductions in match load due to match-specific factors, and may reflect a depletion of glycogen stores in later match stages (Krustrup et al., 2010). It has been inferred that NMF contributes to the increased number of injuries in later match stages as over half of injuries occur in the 2nd half of match-play in adolescent female soccer (Khodaee et al., 2017), a part of the match during which the symptoms of acute match fatigue become prominent as observed in decreased match performance (Mohr et al., 2003, 2005).

However, it is still important to assess individual neuromuscular responses to match-play separate from changes in sports performance, as various external factors such as opposition team have been shown to affect total match load (Trewin et al., 2018b) which may alter neuromuscular responses, even if sports performance reductions are still observed. Yet methods to collect neuromuscular fatigue data can be cost-prohibitive and logistically burdensome (Carling et al., 2018; Thorpe et al., 2017), which may especially apply to female youth soccer teams. Alternatively, exercise assessments of performance as defined in the NMF assessment paradigm (Knicker et al., 2011) are instead utilised to measure neuromuscular response.

Measures of countermovement jump (CMJ) height (Claudino et al., 2017), reactive strength index (RSI) from maximal hop tests, and leg stiffness from submaximal hop tests (Lloyd et al., 2009) are three assessments that have previously been utilised for the purpose of assessing neuromuscular responses in athletes, including in youth athletes. These measures represent neuromuscular attributes including lower limb power and the stretch-shortening cycle (SSC) (Lloyd et al., 2011; Oliver et al., 2015), discussed in more detail in Chapter 2 (Section 2.4.3.2 Measures of fatigue and neuromuscular response in female soccer). In previous studies, tests for CMJ, RSI, and leg stiffness have been shown to be reliable (Claudino et al., 2017; De Ste Croix et al., 2016; Flanagan et al., 2008; Lloyd et al., 2009) and do not require extensive equipment or logistics to complete measures shortly after exercise (Carling et al., 2018; Thorpe et al., 2017). These exercise tests result in minimal additional fatigue compared to sprint or aerobic tests when assessing athletes post-match (Carling et al., 2018; Twist & Highton, 2013), are specific to testing lower limb function

(Hogarth et al., 2014) and thus applicable to soccer, and allow for practical, cost-effective, and efficient testing of neuromuscular response in multiple players in a single team (Carling et al., 2018; Hogarth et al., 2014).

In adult female soccer, CMJ response to match-play is varied with maintenance of CMJ response from pre- to post-match observed in NCAA match-play where substitutes were utilised (Hoffman et al., 2003) but decreases in CMJ height in response to friendly match-play in high-level domestic female players (Andersson et al., 2008). However, these studies were limited to the evaluation of one or two matches. In adolescent female soccer players, a study utilising CMJ tests observed a positive increase in CMJ measures in response to simulated match-play (Wright et al., 2017). Further studies have shown fatigue occurs in response to simulated match load in adolescent female soccer players (De Ste Croix et al., 2015) and that a neuromuscular response in the form of altered leg stiffness can be observed in post-exercise fatigued states (De Ste Croix et al., 2016). These studies, however, were limited to using soccer-specific fatiguing exercise protocols (De Ste Croix et al., 2015, 2016; Wright et al., 2017). Neuromuscular responses have not been evaluated in real match-play in an adolescent female population.

Therefore, the aim of the current study was to evaluate neuromuscular responses to regular-season match load in a cohort of adolescent female soccer players. The effect of match load variables (Chapter 5), in particular high-speed and high-intensity activity, on neuromuscular response is examined. Differences in neuromuscular responses between full-match and substitution conditions as described in Chapter 5 are also explored.

6.2 Methods

6.2.1 Experimental approach to the problem

To evaluate the neuromuscular response to match-play in adolescent female soccer players, pre- and post-match neuromuscular response exercise tests were used to assess 36 participants across 20 matches. CMJ height, RSI, and relative leg stiffness measurements were assessed for differences in FULL and SUB conditions, position, maturation status, and chronological age. Pre- to post-match changes in neuromuscular responses were assessed for relationships with match load variables based on a positive or negative neuromuscular response. For each test, neuromuscular responses per match were also examined. The aims of this study fulfil research objective 3 to examine the effects of high-intensity movement, accelerations, and decelerations on neuromuscular response, and research objective 4, to explore differences in neuromuscular response between substitutes and full-match players in consideration of substitution rules in youth female soccer.

6.2.2 Participants

The 36 participants in the current study are the same as in Chapter 5, from two Regional Talent Clubs (RTCs) U16 teams, Team A and Team B. Participant anthropometrics per team are shown in Table 6.1. The University of Gloucestershire Research Ethics Committee evaluated and approved the protocols in these studies. Coaches and the respective heads of the RTCs were informed of the procedures and consented to pre- and post-match testing. Participants and their parent or guardian gave written consent for the participant's anonymised data to be used in this study. All data were stored and processed in accordance with the General Data Protection Regulation (GDPR). For the 24 hours prior to a match, participants were provided RTC-developed guides and were instructed by coaches and RTC support staff to use rest and recovery strategies, to avoid strenuous activity before a match, and to have an appropriate diet for pre-match preparation. No restrictions were placed on training or diet as the purpose of the study was to evaluate neuromuscular response in the course of a normal match. Only participants who were deemed fit to fully take part in a match by RTC medical staff were included in the study and completed pre-match testing. Participants who were injured in the course of the match or deemed unfit to take part in post-match testing by RTC medical staff were excluded from post-match testing.

A total of 211 individual player-sessions were collected with 36 participants over 20 matches, including pre- and post-match neuromuscular response test (NMRT) results and match load data. An average of 5.9 player-sessions were collected per player (range: 2 – 11).

In Chapter 5, position-specific match loads were observed. However, participants did not always specialise in a playing position, which resulted in match observations (n = 20) where participants changed positions during a match (i.e. Midfield to Defender). Twenty-one such match observations were taken; however, one player did not complete post-match NMRT due to an injury. As these position changes likely resulted in match loads that may not be typical of one position, these player-sessions were considered in a separate position category (Mix). The remaining player-sessions were grouped into Forward (n = 42), Midfield (n = 77), and Defender (n = 72) categories. Additionally, player-sessions were also categorised as full-match (FULL, n = 95) or substitute (SUB, n = 116). Participants and player-sessions per substitution status and position are displayed in Table 6.2.

Participants were placed into the U16 age group by chronological age from August 31 of the season for which they registered (e.g. August 31, 2017 of the 2017 – 2018 season) (The English Football Association, 2017a). In all RTCs, U16 teams consist of two chronological age groups that are 14 years of age or 15 years of age at the beginning of the season. In the current study, participants were considered as Year 1 players (n = 23) if they were 14 years of age or Year 2 players (n = 21) if they were 15 years of age at the beginning of the season in which the match testing took place. Maturation status was assessed for each participant using measures of body mass, height, and leg length to calculate the age of peak height velocity (PHV) and maturational offset based on participant age from PHV (Mirwald et al., 2002). Chronological age and maturation groups did not overlap. Participants were grouped according to maturational offset of <2.5 years post-PHV (Mat 1, n = 25), or ≥2.5 years post-PHV (Mat 2, n = 15) if players were considered closer to 2 years post-PHV or 3 years post-PHV; only three players were determined to be less than 2 years post-PHV. For participants that took part in the study in more than one football season, anthropometric measurements were taken and used for each season, resulting in group numbers greater than numbers of participants. Participants and player-sessions per chronological age group and maturation status are displayed in Table 6.2.

Table 6.1 Participant anthropometrics for Team A and Team B

	Team A	Team B
Number of participants	14	22
Age (years)	14.98 ± 0.70	15.28 ± 0.64
Weight (kg)	57.2 ± 6.9	55.8 ± 6.3
Height (cm)	160.8 ± 5.3	162.8 ± 5.3
Sitting Height (cm)	83.4 ± 4.6	83.5 ± 3.3
Leg length (cm)	77.4 ± 3.2	79.2 ± 4.3
Age at Peak Height Velocity (years)	12.9 ± 0.4	12.9 ± 0.4
Maturational Offset (years)	2.1 ± 0.6	2.4 ± 0.5

Table 6.2 Independent variables for between-group comparisons with participant and player-sessions

		Participants (n)	Mean player-sessions per participant	Range player-sessions per participant
		36	5.9	2 - 11
Independent variable	Description			
Substitution Status	FULL	28	3.4	1 - 8
	SUB	33	3.5	1 - 8
Position	Forward	12	3.5	1 - 9
	Midfield	23	3.3	1 - 9
	Defender	16	4.5	1 - 9
	Mix	15	1.3	1 - 3
Chronological Age	Year 1	23	5.1	1 - 9
	Year 2	21	4.4	1 - 8
Maturation Status	Mat 1	25	5.5	2 - 9
	Mat 2	15	4.9	1 - 9

6.2.3 Matches and neuromuscular response testing

Match testing was conducted for 9 matches with Team A and 11 matches with Team B, taking place during the normal competitive season, with match testing taking place from late September to November and from February to May. Matches included regularly scheduled league matches, cup matches, and friendly matches played against other RTCs during the 2017-2018 and 2018-2019 seasons. A summary of match details including match outcomes for each team is provided in Table 6.3.

Table 6.3 Match details for Team A and Team B

	Team A	Team B	Total
# of matches	9	11	20
Played on Grass	9	9	18
Played on 3G	0	2	2
League	3	5	8
Cup	0	3	3
Friendly	6	3	9
Win	6	6	12
Loss	2	3	5
Draw	1	2	3
Morning Start (9:30-11:59)	9	9	18
Afternoon Start (12:00 – 16:00)	0	2	2
# of days between matches (range), 2017-2018, Feb - May	n/a	24.5 (14-35)	
# of days between matches (range), 2018-2019 1st period, Sep - Nov	10.5 (7-21)	42 (42)	
# of days between matches (range), 2018-2019 2nd period, Feb - May	14 (7-28)	15.4 (7-28)	

The NMRTs were conducted using SmartJump mobile contact mats (Fusion Sport, Queensland, Australia) in the following order: a maximal hop test, a submaximal hop test, and a without-arms countermovement jump (CMJ) test. Detailed procedures and reliability and validity of each test are described in Chapter 3 (Section 3.3.2 Neuromuscular response testing), including calculations of jump height — used for the maximal hop test and the CMJ test — and the reactive strength index (RSI) (Section 3.3.2.1 Maximal hop test); and leg stiffness and relative leg stiffness (Section 3.3.2.2 Submaximal hop test). Participants were familiarised with the NMRT procedures and techniques prior to match testing during previous training sessions and were re-familiarised with the NMRTs on the day of the first match when testing occurred, immediately prior to testing. At subsequent matches, participants did not require re-familiarisation. At each match, the same instructions were provided for the NMRTs and participants were encouraged by the researcher to promote adherence to correct procedure. Participants were asked to reperform the test if the correct procedure was not followed. A rest period of at least one minute was observed between each test. NMRTs were conducted approximately 45 minutes prior to matches and before the team warm up, and approximately 10 minutes post-match after a brief cool down and return to the player changing area.

Pre- and post-match test data from the SmartJump system was uploaded to the SmartSpeed Fusion cloud-based website and downloaded as CSV files for analysis using Excel. For the CMJ, jump height (JH, cm) was calculated using flight time (Ft, ms). The average of the three CMJs was used for analysis, as average CMJ height has been shown to be sensitive to changes in neuromuscular response compared with highest CMJ height (Claudino et al., 2017). The RSI was calculated by using flight time to calculate jump height, then divided by contact time (Ct, ms) (Flanagan & Comyns, 2008) using the JH and Ct from four maximal hops which were then averaged (Oliver et al., 2015). Data from the submaximal hop test included Ft and Ct from 10 consecutive hops which were used to calculate leg stiffness (Dalleau et al., 2004). Relative leg stiffness (RelStiff, dimensionless) was then calculated by multiplying leg stiffness by a factor of the participant’s body mass and leg length (McMahon & Cheng, 1990). Variables used from each NMRT are listed in Table 6.4.

Match load variables from Chapter 5 used for analysis in the current study are listed in Table 6.5. High-speed activity (HSA) was included as a variable, which accounts for running distances above 4.3 $m \cdot s^{-1}$, as changes in HSA have previously been considered in studies of fatigue and match load in female soccer (Andersson et al., 2010; Mohr et al., 2003, 2008). As in Chapter 5, in order to account for differences in time played between FULL and SUB match observations, relative data were calculated from match load variables averaged over individual time played (variable per minute). Between-half differences of match variables were also calculated.

Table 6.4 Measures and calculated variables from each NMRT

Neuromuscular Response Test	Variable (units)
Countermovement jump test	Jump height (cm)
Maximal hop test	Reactive strength index
Submaximal hop test	Flight time (ms)
	Contact time (ms)
	Relative leg stiffness

Table 6.5 Match load variables from player-sessions

Variable	Unit of measurement
Total distance (TOTAL)	m
Time played	min
Work rate (WR)	$m \cdot min^{-1}$
Sprint distance (SPR, $\geq 5.6\ m \cdot s^{-1}$)	m
High-speed activity distance (HSA, $\geq 4.3\ m \cdot s^{-1}$) (combined SPR and HSR)	m
Low-speed running distance (LOW, $<4.3\ m \cdot s^{-1}$)	m
# of accelerations (ACCEL, $>1.0\ m \cdot s^{-2}$)	
# of decelerations (DECEL, $<-1.0\ m \cdot s^{-2}$)	
Average heart rate (average HR)	beats per minute

6.2.4 Statistical analysis

Statistical analysis was conducted using Excel (Microsoft, Redmond, WA) and SPSS (Version 24, SPSS Inc., Chicago, IL). Statistical significance for was set at $p < 0.05$. Where reported, data are presented as mean ± standard deviation (SD). Mean differences and 90% confidence intervals (CI) are presented as positive where test measures increased from pre- to post-match and negative where measures decreased from pre- to post-match.

All data were assessed for normality using skewness and kurtosis; values for asymmetry and kurtosis between -2 and +2 are considered acceptable to prove normal distribution (George & Mallery, 2010). In the event of a possible violation of assumption of normality, data were re-analysed using the nonparametric equivalent of the test which did not change results, with one exception as noted for comparison of pre- to post-match Ft for all player-sessions. Levene's test was used to assess the assumption of equal variance for each variable. Bonferroni adjustments were used where equal variances were assumed, and Dunnett's T3 adjustments were used where equal variances were not assumed. Magnitudes of correlation for Pearson's were interpreted as very small (0.0-0.1), small (0.1-0.3), moderate

(0.3-0.5), large (0.5-0.7), very large (0.7-0.9), and nearly perfect (0.9-1) (W.G. Hopkins, 2002). Where reported, Cohen's *d* for effect size was considered small, moderate, large, very large, and extremely large with values greater than 0.1, 0.3, 0.5, 0.7, and 0.9, respectively (Hopkins et al., 2009). Effect sizes for repeated-measures ANOVAs and one-way ANCOVAs are reported as partial eta squared (η^2) and interpreted as small ($0.01 \leq \eta^2 < 0.06$), moderate ($0.06 \leq \eta^2 < 0.14$), or large ($\eta^2 \geq 0.14$) (Cohen, 1988).

6.2.4.1 Pre- to post-match differences and effect of independent variables on neuromuscular response

Paired t-tests were used to compare within-participant pre- and post-match NMRT measures for all player-sessions and for each independent variable group. To examine the effect of maturation, chronological age, position, and substitution status on NMRT measures, mixed-method repeated measures ANOVAs were conducted for each NMRT measure to evaluate main effects and interaction effects of each independent variable. Independent samples tests were conducted to compare pre-match NMRT measures between substitution status groups.

To evaluate the effects of maturation, chronological age, and position on the pre- to post-match rates of change (differences) of each NMRT measure, one-way ANCOVAs were conducted using time played per player-session as a covariate to account for the differences in time played due to substitutions. In the event that the assumptions for ANCOVA were violated, a one-way ANOVA was conducted to compare groups for chronological age for Ft. To evaluate the effect of substitution status on the pre- to post-match rates of change of each

NMRT measure, independent t-tests were conducted. A covariate was not included in the model testing substitution status as substitution status is related to time played.

As use of substitutions were observed in Chapter 5 to mitigate reductions in match load in Forward and Defender players, a 4 x 2 (position x substitution status) mixed-model ANCOVA was also conducted to assess the interaction of these position and substitution status on pre- to post-match rates of change of NMRT measures. Time played was used as a covariate to control for effects of the differences in substitution time played.

6.2.4.2 Effects of match load variables on neuromuscular response

To examine the effects of match load on neuromuscular response, NMRT measures were converted into a normalised z-score using the formula z-score = (participant test score – group mean score)/SD as calculated in SPSS and differences from pre- to post-match were determined. A negative difference between z-scores denoted a decrease or negative change in the NMR measure and a positive difference denoted an increase or positive change in the NMR measure. The smallest worthwhile change (SWC) was determined from the z-scores differences for each NMRT using the formula SWC = between-participant SD x 0.2. NMR z-scores that were greater or less than the SWC were deemed to be meaningful changes in pre- to post-match NMR. Data that were outside the SWC were subsequently used for analysis, including 137 cases for CMJ, 131 cases for RSI, and 157 cases for RelStiff. Data were analysed using Pearson’s correlation with match load variables from Chapter 5 that were logarithmically transformed. Match load variables used in analysis included time played, work rate, and relative LOW, SPR, HSA, ACCEL, and DECEL. NMR z-scores differences were also analysed via Pearson’s correlation with 1st to 2nd half changes in WR and in relative

LOW, SPR, HSA, ACCEL, and DECEL that were converted into normalised z-scores due to negative values in 1st to 2nd half differences. These correlation analyses were also conducted for NMR z-score differences within full-match and substitute condition sub-groups.

6.2.4.3 Neuromuscular response per match

To examine per match response, paired t-tests were used to determine the significance of pre- to post-match differences in NMRT measures. The mean pre- to post-match differences were calculated along with 90% confidence intervals. To qualitatively examine the changes per team for each match, inferential statistics were employed using an online spreadsheet (Hopkins, 2007) to calculate the probabilistic inference that the pre- to post-match difference of each NMRT measure is greater than the smallest worthwhile effect (SWE). The SWE was determined as the product of 0.2 and the standard deviation of each pre-match NMRT measure. Magnitude-based inferences were determined on the probability of a change being greater than the SWE using ranges of 25 – 75% (possibly), 75 – 95% (likely), 95 – 99.5% (very likely), and 100% (most likely) (Hopkins et al., 2009). An effect was deemed as unclear if there were greater than 5% chances of both positive and negative effects, shown graphically as the 90% confidence interval overlapping the SWE. In the event an effect was clear, the categorical effect (negative, trivial, or positive) was reported for the greatest probable outcome (Hopkins, 2007).

6.3 Results

6.3.1 Pre- to post-match differences and effect of independent variables on neuromuscular response

Results from the CMJ, maximal hop, and submaximal hop for all player-sessions are displayed in Table 6.6. Mean pre- to post-match differences are also displayed along with paired t-tests results comparing pre- and post-match variable measures. Significant differences were observed between pre- and post-match tests for the submaximal hop variables Ct, Ft, and RelStiff in analysis of all player-sessions, with a mean increase in Ct and mean decrease in Ft and RelStiff observed.

Table 6.6 Results (mean ± SD) and comparisons for all player-sessions for each NMRT

		n	Pre	Post	Mean Δ	p-value	Cohen's *d*
ALL	CMJ	211	27.04 ± 3.53	26.86 ± 3.76	-0.18 ± 2.35	0.266	0.05
	RSI	195	1.01 ± 0.33	1.02 ± 0.37	0.01 ± 0.33	0.726	0.02
	Ct	210	185.1 ± 28.9	189.5 ± 25.5	4.5 ± 21.3	0.003*	0.16
	Ft	210	314.6 ± 33.56	311.2 ± 32.2	-3.5 ± 26.3	0.009*^{NP}	0.11
	RelStiff	210	34.13 ± 8.40	28.79 ± 10.46	-5.34 ± 8.21	<0.001*	0.56

n = number of player-sessions per test; Pre = pre-match measure; Post = post-match measure; Mean Δ = mean difference between post- and pre-match measures; CMJ = countermovement jump height (cm); RSI = reactive strength index; Ct = average contact time (ms) from submaximal hop; Ft = average flight time (ms) from submaximal hop; RelStiff = average relative leg stiffness; ^{NP} = nonparametric test; * = denotes significant difference between pre- and post-match results, $p < 0.05$.

Pre- and post-match measures and results of the repeated measures ANOVA are given for each independent variable: for substitution status, in Table 6.7; for position, in Table 6.9, for chronological age, in Table 6.11, and for maturation status in Table 6.13. Results of comparisons of pre-match NMRT measures between substitution status groups are also given in Table 6.7. Interaction effect between pre- and post-match and main effects for between-group differences for each independent variable on NMRT measures are displayed along with pairwise comparisons where significant between-group main effects were observed. Mean differences (rates of change) and results of the independent t-tests for between group differences for substitution status are displayed in Table 6.8. Mean differences and results of the one-way ANCOVAs comparing rates of change between groups are given for position in Table 6.10, chronological age in Table 6.12, and maturation status in Table 6.14. In all ANCOVAs, no significant main effects were observed for Time Played.

For substitution status, a significant difference was observed between FULL and SUB measures of pre-match CMJ, with FULL players having higher baseline measures. Significant pre- to post-match differences were observed for Ct and Ft for FULL player-sessions with increased Ct and decreased Ft, both with small effect sizes ($d > 0.1$). Decreased RelStiff was also observed for both FULL and SUB player-sessions, with moderate ($d = 0.49$) and large ($d = 0.63$) effect sizes, respectively. Significant main effects were observed for CMJ height and RelStiff, with higher CMJ height ($p = 0.003$) and higher RelStiff ($p = 0.022$) observed for FULL player-sessions compared to SUB player-sessions, both with a small effect size ($\eta^2 < 0.06$). No significant between-group differences were observed for rates of change in NMRT measures.

For position, significant differences pre- to post-match were observed for Ct in Forward and Defender player-sessions with increased Ct for both groups, with small effect sizes ($d > 0.1$). Significant pre- to post-match differences were observed for all position groups for RelStiff, with decreased RelStiff. Effect sizes were large for all position groups (*d*

> 0.5). No significant interaction or main effects were observed for NMRT measures between positions and no significant main effects were observed for rates of change in NMRT measures between positions.

For chronological age, significant differences were observed pre- to post-match for CMJ and Ct for Year 2 player-sessions, with decreased CMJ height (small effect size, *d* = 0.13) and increased Ct (small effect size, *d* = 0.22). Pre- to post-match measures of CMJ for chronological age are presented in Figure 6.1. Significant differences were observed for RelStiff for both Year 1 and Year 2 player sessions with decreases in RelStiff, both with large effect sizes (d > 0.5). Significant main effects were observed for chronological age, with player-sessions from Year 2 with higher CMJ height (p = 0.043) compared to Year 1, with a small effect size ($\eta^2 < 0.06$). However, the Year 1 group had significantly longer Ct (p = 0.001), longer Ft (p = 0.002) and higher RelStiff (p = 0.007) compared to Year 2, also with small effect sizes ($\eta^2 < 0.06$). No significant main effects were observed for rates of change between chronological age groups.

For maturation status, a significant difference was observed for CMJ for Mat 2 with decreases in pre- to post-match CMJ height, with a small effect size (*d* = 0.16). Significant differences were also observed for both Mat 1 and Mat 2 for increased Ct (small effect sizes, *d* > 0.1) and decreased RelStiff pre- to post-match (large effect sizes, *d* > 0.5). Pre- to post-match measures of CMJ for maturation status are presented in Figure 6.1. A significant main effect for CMJ was also observed for maturation status, with high CMJ height for Mat 2 (p <0.001) compared to Mat 1, with a moderate effect size ($\eta^2 = 0.097$). A significant interaction effect was also noted for maturation (p = 0.038) with Mat 2 decreasing pre- to post-match

CMJ and Mat 1 increasing pre- to post-match CMJ, with a small effect size ($\eta^2 = 0.020$). Subsequently, a significant difference in the rates of change was observed between maturation groups ($p = 0.040$) with a small effect size ($\eta^2 = 0.020$).

Results of the mixed-model ANCOVA for position and substitution status interaction on rates of change to NMRT measures are displayed in Table 6.15 No significant interactions for substitution status with position (substitution*position) were observed.

Table 6.7 Pre- and post-match measures (mean ± SD) for FULL and SUB player-session groups with significant difference pre- to post-match noted. Results of repeated measures ANOVA are shown, including interaction effects for repeated measures and main effects of substitution status.

	FULL				SUB				Interaction Effect	Main Effect	
	n	Pre	Post	*d*	n	Pre	Post	*d*	(p-value) Partial η^2	(p-value) Partial η^2	Pairwise Comparison
CMJ	95	27.85 ± 3.36**	27.58 ± 3.75		116	26.37 ± 3.54**	26.27 ± 3.68		(0.617) 0.001	(0.003)^ 0.041	FULL > SUB
RSI	88	1.04 ± 0.36	1.07 ± 0.38		107	0.98 ± 0.30	0.97 ± 0.36		(0.542) 0.002	(0.060) 0.018	NS
Ct	94	182.6 ± 31.7	189.3 ± 25.5*	0.23	116	187 ± 26.4	189.8 ± 25.6		(0.186) 0.008	(0.484) 0.002	NS
Ft	94	317.1 ± 36.4	311 ± 31.7*	0.18	116	312.6 ± 31.0	311.3 ± 32.8		(0.196) 0.008	(0.620) 0.001	NS
RelStiff	94	35.36 ± 9.24	30.56 ± 10.12*	0.49	116	33.13 ± 7.56	27.36 ± 10.54*	0.63	(0.392) 0.004	(0.022)^ 0.025	FULL > SUB

n = number of player-sessions per test; Pre = pre-match measure; Post = post-match measures; *d* = Cohen's d for effect size; CMJ = countermovement jump height (cm); RSI = reactive strength index; Ct = average contact time (ms) from submaximal hop; Ft = average flight time (ms) from submaximal hop; RelStiff = average relative leg stiffness; ** = denotes significant differences between FULL and SUB pre-match results, $p < 0.05$; * = denotes significant difference between pre- and post-match results, $p < 0.05$; ^ = denotes significant main effect; Partial η2 – partial eta squared for effect size; NS – p-value not significant.

Table 6.8 Mean differences (mean ± SD) between pre- and post-match measures and results of independent t-tests comparing rate of change for FULL and SUB groups.

	FULL Mean Δ	SUB Mean Δ	Pairwise Comparison (p-value)
CMJ	-0.27 ± 2.63	-0.11 ± 2.09	(0.630)
RSI	0.02 ± 0.33	0.0 ± 0.33	(0.540)
Ct	6.6 ± 20.1	2.7 ± 22.1	(0.200)
Ft	-6.1 ± 24.4	-1.3 ± 27.8	(0.100)
RelStiff	-4.8 ± 7.36	-5.77 ± 8.85	(0.550)

Mean Δ = mean difference between post- and pre-match measures; CMJ = countermovement jump height (cm); RSI = reactive strength index; Ct = average contact time (ms) from submaximal hop; Ft = average flight time (ms) from submaximal hop; RelStiff = average relative leg stiffness; * = denotes significant difference between substitution status groups, $p < 0.05$.

Table 6.9 Pre- and post-match measures (mean ± SD) for position groups with significant difference pre- to post-match noted. Results of repeated measures ANOVA are shown, including interaction effects for repeated measures and main effects of position.

	Forward				Midfield				Defender				Mix				Interaction Effect	Main Effect	
	n	Pre	Post	*d*	n	Pre	Post	*d*	n	Pre	Post	*d*	n	Pre	Post	*d*	(p-value) Partial η^2	(p-value) Partial η^2	Pairwise Comparison
CMJ	42	27.49 ± 3.80	26.95 ± 3.73		77	26.48 ± 3.21	26.29 ± 3.65		72	27.63 ± 3.66	27.56 ± 3.83		20	26.12 ± 3.39	26.31 ± 3.76		(0.664) 0.008	(0.125) 0.027	NS
RSI	38	0.99 ± 0.25	1.03 ± 0.32		71	1.03 ± 0.34	1.00 ± 0.41		67	1.00 ± 0.34	1.04 ± 0.35		19	0.98 ± 0.35	0.94 ± 0.40		(0.588) 0.010	(0.884) 0.003	NS
Ct	41	176.6 ± 29.5	184.9 ± 29.1*	0.28	77	187.5 ± 27.6	188.1 ± 20.5		72	186.1 ± 29.7	193.7 ± 28.7*	0.26	20	189.3 ± 27.9	189.4 ± 22.4		(0.100) 0.030	(0.290) 0.018	NS
Ft	41	324.2 ± 29.8	316.1 ± 34.7		77	310.2 ± 29.9	310.7 ± 25.7		72	313.8 ± 39.1	308.4 ± 38.3		20	314.8 ± 31.0	312.6 ± 26.2		(0.328) 0.017	(0.370) 0.015	NS
RelStiff	41	38.01 ± 9.91	31.15 ± 12.41*	0.61	77	32.68 ± 7.42	28.05 ± 8.92*	0.56	72	33.92 ± 8.12	28.63 ± 10.89*	0.55	20	32.5 ± 7.70	27.39 ± 10.02*	0.57	(0.578) 0.010	(0.060) 0.035	NS

n = number of player-sessions per test; Pre = pre-match measure; Post = post-match measures; *d* = Cohen's d for effect size; CMJ = countermovement jump height (cm); RSI = reactive strength index; Ct = average contact time (ms) from submaximal hop; Ft = average flight time (ms) from submaximal hop; RelStiff = average relative leg stiffness; * = denotes significant difference between pre- and post-match results, $p < 0.05$; Partial η2 – partial eta squared for effect size. NS – p-value not significant.

Table 6.10 Mean differences (mean ± SD) between pre- and post-match measures and ANCOVA results comparing rate of change for position groups.

	Forward	Midfield	Defender	Mix	Main Effect	
	Mean Δ	Mean Δ	Mean Δ	Mean Δ	(p-value)	Partial η^2
CMJ	-0.53 ± 2.48	-0.18 ± 2.15	-0.07 ± 2.62	0.18 ± 1.73	(0.952)	0.002
RSI	0.04 ± 0.26	-0.02 ± 0.36	0.04 ± 0.33	-0.04 ± 0.3	(0.618)	0.009
Ct	8.3 ± 23.5	0.6 ± 22.4	7.7 ± 18.4	0.2 ± 19.9	(0.388)	0.015
Ft	-8.1 ± 25.9	0.5 ± 25.2	-5.4 ± 28.9	-2.2 ± 20.8	(0.469)	0.013
RelStiff	-6.86 ± 8.71	-4.63 ± 8.18	-5.29 ± 8.43	-5.11 ± 6.49	(0.944)	0.002

Mean Δ = mean difference between post- and pre-match measures; CMJ = countermovement jump height (cm); RSI = reactive strength index; Ct = average contact time (ms) from submaximal hop; Ft = average flight time (ms) from submaximal hop; RelStiff = average relative leg stiffness; * = denotes significant difference between position groups, $p < 0.05$; Partial η2 – partial eta squared for effect size.

Table 6.11 Pre- and post-match measures (mean ± SD) for chronological age player-session groups with significant difference pre- to post-match noted. Results of repeated measures ANOVA are shown, including interaction effects for repeated measures and main effects of chronological age.

	Year 1				Year 2				Interaction Effect	Main Effect	
	n	Pre	Post	*d*	n	Pre	Post	*d*	(p-value) Partial η^2	(p-value) Partial η^2	Pairwise Comparison
CMJ	117	26.48 ± 3.12	26.56 ± 3.61		94	27.73 ± 3.88	27.23 ± 3.92*	0.13	(0.074) 0.015	(0.043)^ 0.019	Year 2 > Year 1
RSI	108	1.02 ± 0.28	1.03 ± 0.35		87	0.99 ± 0.37	1.00 ± 0.39		(0.835) 0.000	(0.515) 0.002	NS
Ct	116	180.3 ± 29.8	183.8 ± 24.2		94	191.0 ± 26.26	196.6 ± 25.4*	0.22	(0.483) 0.002	(0.001)^ 0.055	Year 2 > Year 1
Ft	116	319.5 ± 32.8	317.7 ± 29.3		94	308.6 ± 33.6	303.1 ± 34.0		(0.305) 0.005	(0.002)^ 0.045	Year 1 > Year 2
RelStiff	116	35.55 ± 8.69	30.25 ± 10.67*	0.54	94	32.38 ± 7.72	27.00 ± 9.94*	0.60	(0.943) 0.000	(0.007)^ 0.035	Year 1 > Year 2

n = number of player-sessions per test; Pre = pre-match measure; Post = post-match measures; *d* = Cohen's d for effect size; CMJ = countermovement jump height (cm); RSI = reactive strength index; Ct = average contact time (ms) from submaximal hop; Ft = average flight time (ms) from submaximal hop; RelStiff = average relative leg stiffness; * = denotes significant difference between pre- and post-match results, $p < 0.05$; ^ = denotes significant main effect, $p < 0.05$; Partial η2 – partial eta squared for effect size; NS – p-value not significant.

Table 6.12 Mean differences (mean ± SD) between pre- and post-match measures and ANCOVA results comparing rate of change for chronological age groups.

	Year1	Year 2	Main Effect	
	Mean Δ	Mean Δ	(p-value)	Partial η^2
CMJ	0.08 ± 2.27	-0.5 ± 2.41	(0.108)	0.013
RSI	0.004 ± 0.33	0.01 ± 0.32	(0.459)	0.003
Ct	3.6 ± 21.9	5.6 ± 20.6	(0.244)	0.007
Ft	-1.8 ± 21.9	-5.5 ± 31.0	(0.305)	0.005^{ANOVA}
RelStiff	-5.3 ± 8.01	-5.38 ± 8.50	(0.438)	0.003

Mean Δ = mean difference between post- and pre-match measures; CMJ = countermovement jump height (cm); RSI = reactive strength index; Ct = average contact time (ms) from submaximal hop; Ft = average flight time (ms) from submaximal hop; RelStiff = average relative leg stiffness; * = denotes significant difference between chronological age groups, $p < 0.05$; $^{\text{ANOVA}}$ = ANOVA result; Partial η2 – partial eta squared for effect size.

Table 6.13 Pre- and post-match measures (mean ± SD) for maturation groups with significant difference pre- to post-match noted. Results of repeated measures ANOVA are shown, including interaction effects for repeated measures and main effects of maturation status.

	Mat 1				Mat 2				Interaction Effect	Main Effect	
	n	Pre	Post	*d*	n	Pre	Post	*d*	(p-value) Partial η^2	(p-value) Partial η^2	Pairwise Comparison
CMJ	138	26.14 ± 3.06	26.2 ± 3.46		73	28.74 ± 3.75	28.1 ± 4.00*	0.16	(0.038)^ 0.020	(<0.001)^ 0.097	Mat 2 > Mat 1
RSI	126	1.00 ± 0.29	1.01 ± 0.34		69	1.02 ± 0.39	1.02 ± 0.42		(0.823) 0.000	(0.705) 0.001	NS
Ct	137	183.9 ± 30.5	188.4 ± 28.2*	0.15	73	187.2 ± 25.7	191.6 ± 19.6*	0.19	(0.976) 0.000	(0.372) 0.004	NS
Ft	137	315.3 ± 34.4	312.6 ± 34.8		73	313.3 ± 32.1	308.4 ± 26.8		(0.559) 0.002	(0.482) 0.002	NS
RelStiff	137	34.41 ± 8.67	28.82 ± 11.33*	0.55	73	33.59 ± 7.90	28.73 ± 8.66*	0.59	(0.547) 0.002	(0.714) 0.001	NS

n = number of player-sessions per test; Pre = pre-match measure; Post = post-match measures; *d* = Cohen’s d for effect size; CMJ = countermovement jump height (cm); RSI = reactive strength index; Ct = average contact time (ms) from submaximal hop; Ft = average flight time (ms) from submaximal hop; RelStiff = average relative leg stiffness; * = denotes significant difference between pre- and post-match results, $p < 0.05$; ^ = denotes significant main effect; Partial η2 – partial eta squared for effect size; NS – p-value not significant.

Table 6.14 Mean differences (mean ± SD) between pre- and post-match measures and ANCOVA results comparing rate of change for maturation status groups.

	Mat 1	Mat 2	Main Effect	
	Mean Δ	Mean Δ	(p-value)	Partial η^2
CMJ	0.06 ± 2.10	-0.64 ± 2.70	(0.040)*	0.020
RSI	0.01 ± 0.31	0.001 ± 0.36	(0.693)	0.001
Ct	4.5 ± 22.6	4.4 ± 18.6	(0.841)	0.000
Ft	-2.7 ± 25.8	-4.9 ± 27.4	(0.595)	0.001
RelStiff	-5.59 ± 8.27	-4.9 ± 8.14	(0.632)	0.001

Mean Δ = mean difference between post- and pre-match measures; CMJ = countermovement jump height (cm); RSI = reactive strength index; Ct = average contact time (ms) from submaximal hop; Ft = average flight time (ms) from submaximal hop; RelStiff = average relative leg stiffness; * = denotes significant difference between maturation status groups, $p < 0.05$; Partial η2 – partial eta squared for effect size.

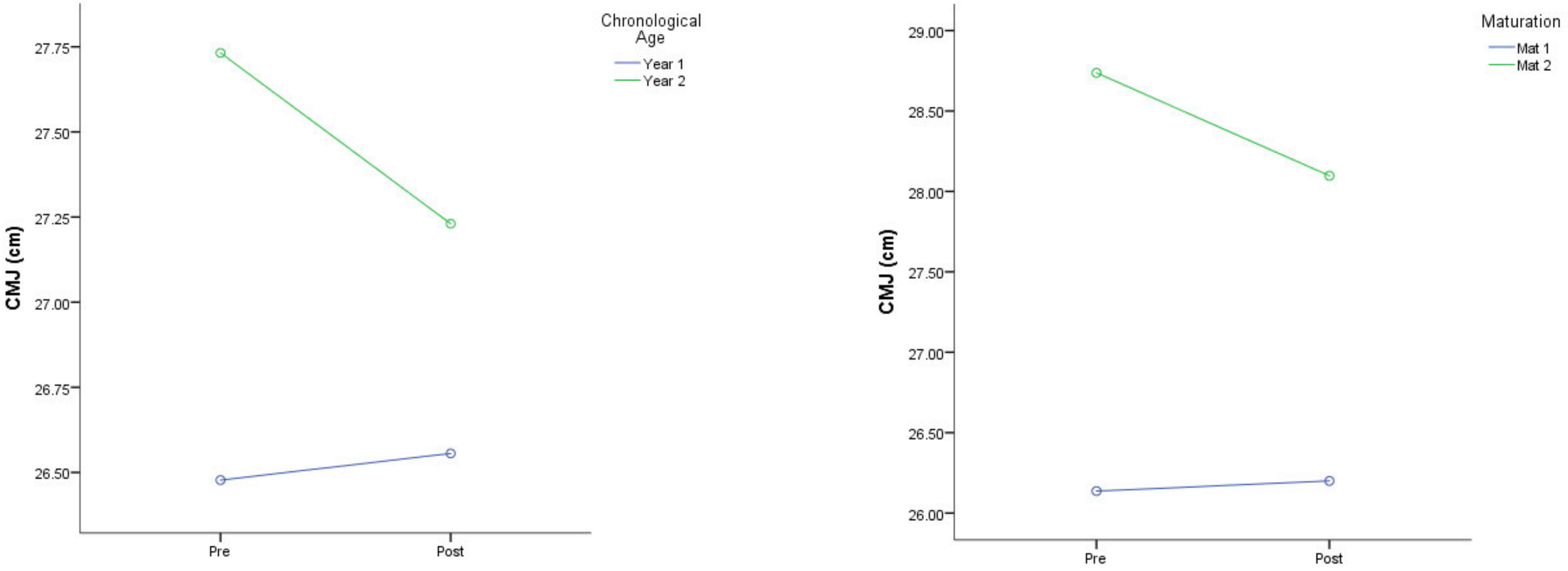


Figure 6.1 Line graphs of pre- to post-match changes of CMJ height (cm) for chronological age and maturation status, demonstrating the significant main effect for between-group measures, the significant main effect for between-group rates of change, and for maturation status, the significant interaction effect between maturation status groups.

Table 6.15 Results of the 4 x 2 mixed-model ANCOVA testing interaction effects for substitution status and position on changes in NMRT measures with time played as covariate.

NMRT measure	F	(p-value)	Partial η2
ΔCMJ	0.96	(0.411)	0.014
ΔRSI	1.26	(0.291)	0.020
ΔCt	0.51	(0.679)	0.007
ΔFt	0.64	(0.592)	0.009
ΔRelStiff	2.46	(0.064)	0.035

Δ CMJ = mean difference countermovement jump height; Δ RSI = mean difference reactive strength index; Δ Ct = mean difference average contact time; Δ Ft = mean difference average flight time; Δ RelStiff = mean difference average relative leg stiffness; * = denotes significant interaction of substitution status*position, $p < 0.05$; Partial η2 – partial eta squared for effect size.

6.3.2 Effects of match load variables on neuromuscular response

Z-score differences per NMR and upper and lower SWC limits are shown in Figure 6.2. The z-score differences within the SWC were not included in analysis. Correlation analyses between NMR z-score differences for RSI and RelStiff did not reveal any significant correlations with time played or relative match load variables. One significant correlation was reported for CMJ with a small negative correlation between CMJ z-score difference and relative DECEL ($r = -0.182$, $p < 0.05$). No significant correlations were reported between NMR z-score differences and 1st to 2nd half match changes in match load. Analysis of full-match and substitute sub-groups similarly did not reveal significant correlations with the exception of a small negative correlation between FULL CMJ z-score difference and relative DECEL ($r = -0.231$, $p < 0.05$). There was no significant correlation between SUB CMJ z-score difference and relative DECEL.

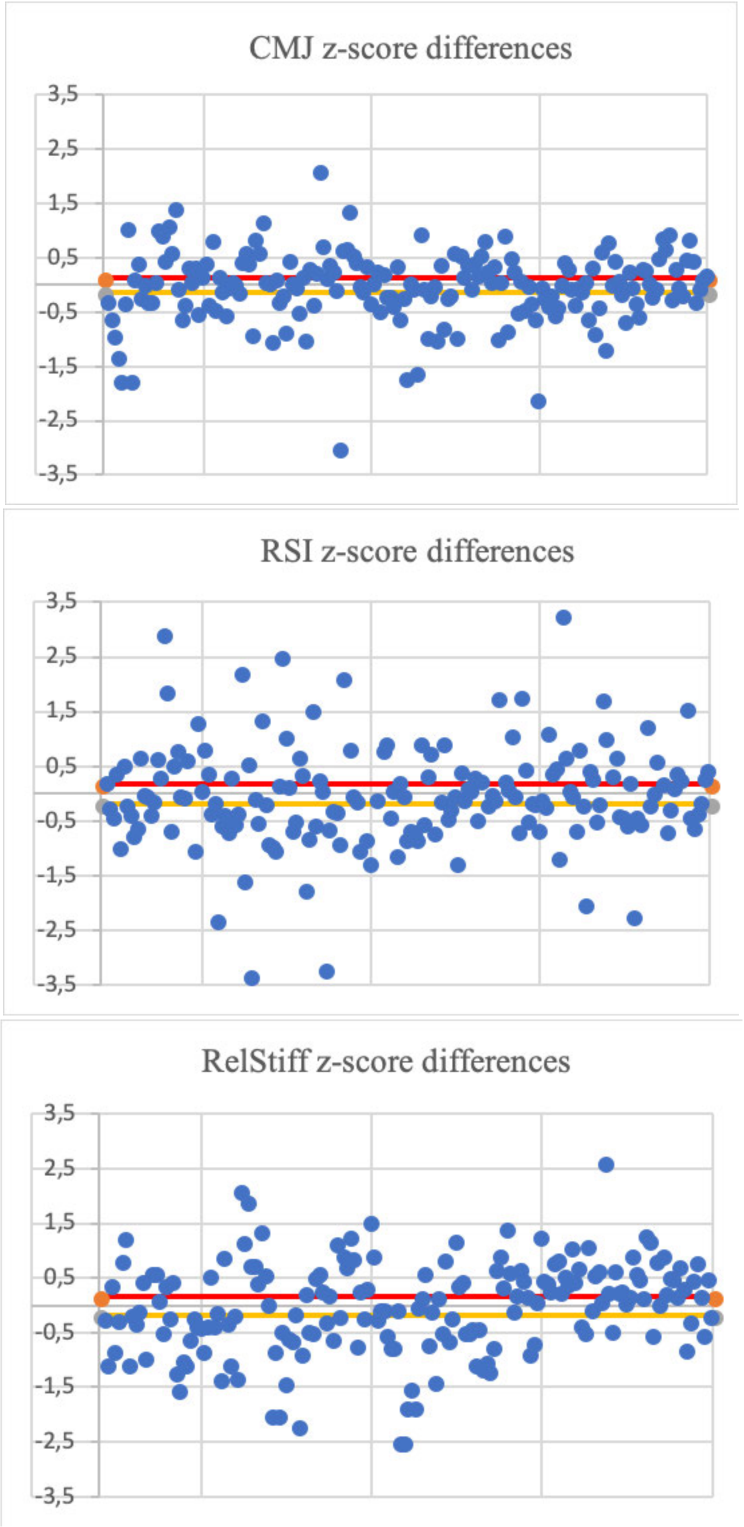
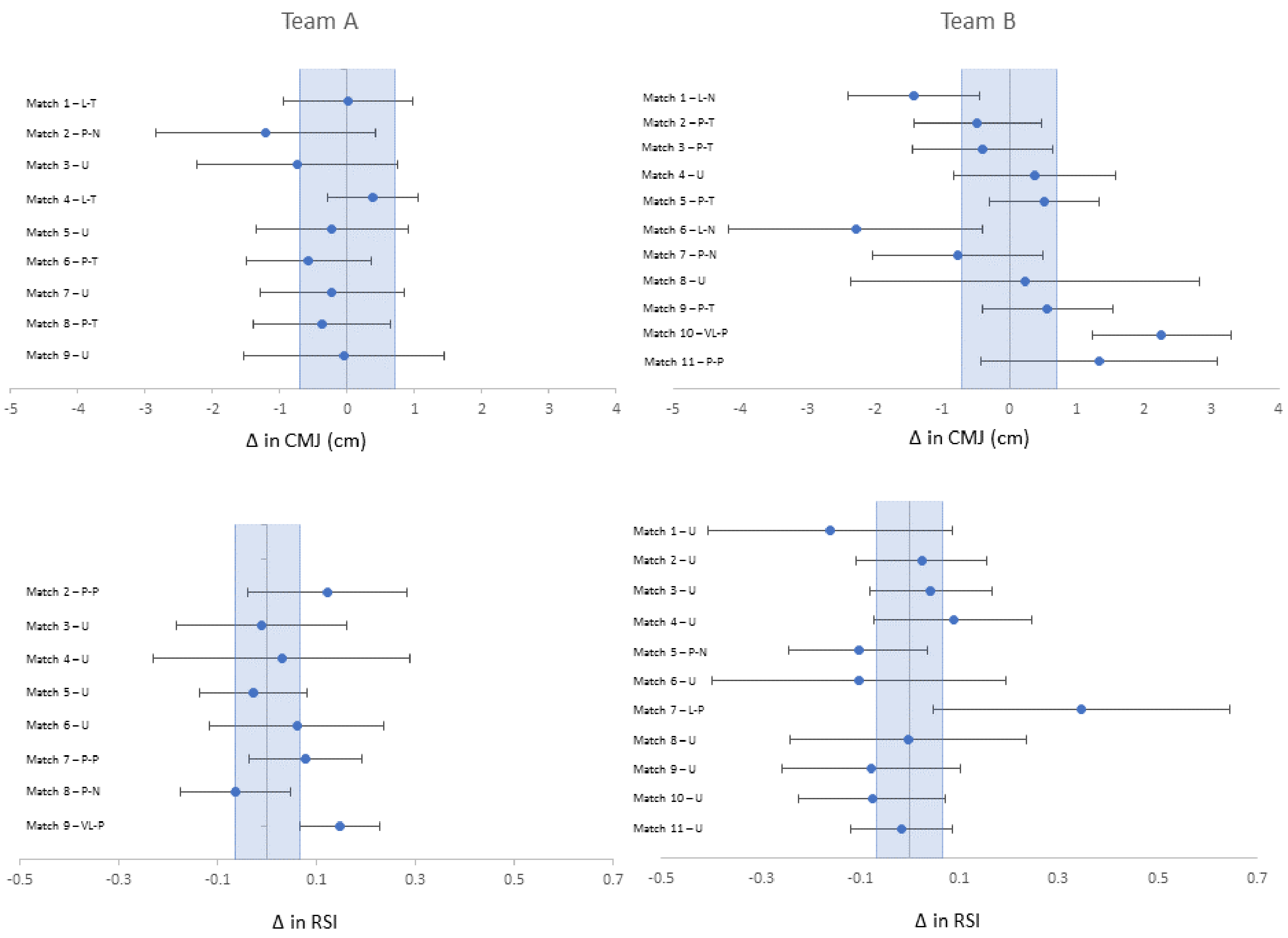


Figure 6.2 Scatterplots of individual Z-score differences per NMR measure with SWC lines (red: upper SWC, yellow: lower SWC)

6.3.3 Neuromuscular response per match

Descriptive statistics for each NMRT measure, statistical significance of differences, and percent for greatest probable outcome are presented for Team A and Team B per match in Appendix 6.1. Mean pre- to post-match differences (± 90% CI) of CMJ, RSI, and RelStiff and inferential outcomes are shown in Figure 6.3 for Team A and Team B per match. Varied responses per team to CMJ and RSI were observed: for Team A, CMJ responses ranged from *possibly negative* to *likely trivial*; for Team B, CMJ responses ranged from *likely negative* to *very likely positive*. For RSI, Team A observed changes ranged from *possibly negative* to *very likely positive*. For RSI for Team B, observed changes also ranged from *possibly negative* to *likely positive*. In both CMJ and RSI, wide confidence intervals were observed for some matches. For RelStiff with Team A, if changes per match were not deemed *unclear*, changes were deemed *possibly or likely negative*. For Team B, if changes per match were not deemed *unclear*, changes ranged from *possibly* to *most likely negative*. For Team B, matches 1, 2, and 3 were deemed *mostly likely negative* and represent RelStiff change for Team B in the first season the study was conducted. A majority of RelStiff changes for Team B were deemed *likely negative*.


Team A
Team B
Match 1 – L-T
Match 2 – P-N
Match 3 – U
Match 4 – L-T
Match 5 – U
Match 6 – P-T
Match 7 – U
Match 8 – P-T
Match 9 – U
-5
-4
-3
-2
-1
0
1
2
3
4
Δ in CMJ (cm)
Match 1 – L-N
Match 2 – P-T
Match 3 – P-T
Match 4 – U
Match 5 – P-T
Match 6 – L-N
Match 7 – P-N
Match 8 – U
Match 9 – P-T
Match 10 – VL-P
Match 11 – P-P
-5
-4
-3
-2
-1
0
1
2
3
4
Δ in CMJ (cm)
Match 2 – P-P
Match 3 – U
Match 4 – U
Match 5 – U
Match 6 – U
Match 7 – P-P
Match 8 – P-N
Match 9 – VL-P
-0.5
-0.3
-0.1
0.1
0.3
0.5
0.7
Δ in RSI
Match 1 – U
Match 2 – U
Match 3 – U
Match 4 – U
Match 5 – P-N
Match 6 – U
Match 7 – L-P
Match 8 – U
Match 9 – U
Match 10 – U
Match 11 – U
-0.5
-0.3
-0.1
0.1
0.3
0.5
0.7
Δ in RSI

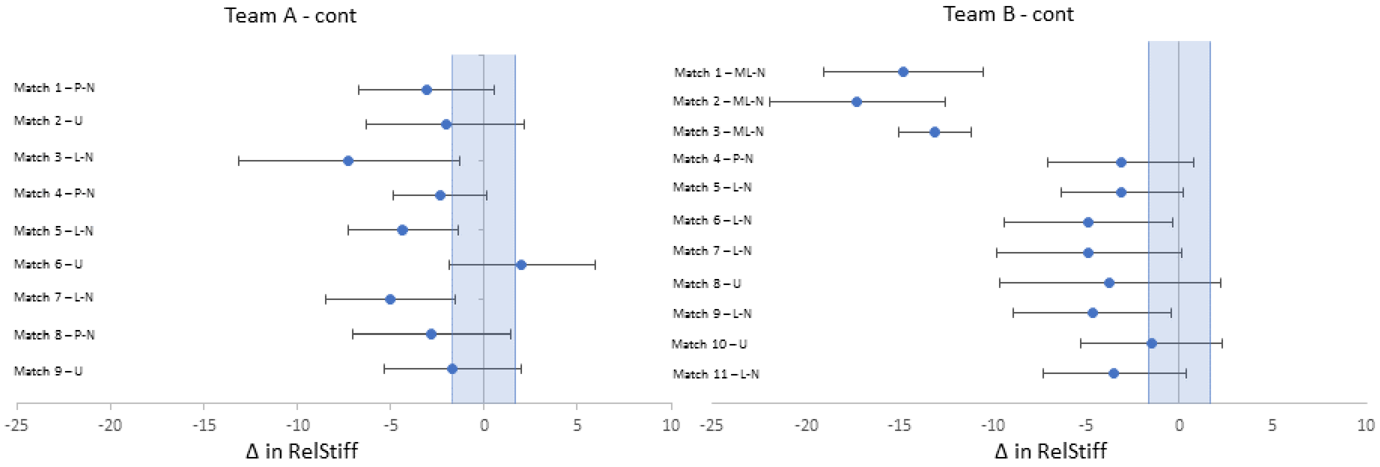


Figure 6.3 Inferential statistics for NMRT measures of CMJ, RSI, and RelStiff per match for Team A and Team B presented as mean differences (±90% CI). Shaded areas represent the smallest worthwhile effect. No Team A, Match 1 results for RSI due to a technical issue. Δ = mean difference; CMJ = countermovement jump; RSI = reactive strength index; RelStiff = relative leg stiffness. For inferential outcome ratings per match: U = unclear; P-T = possibly trivial, L-T = likely trivial; P-N = possibly negative; L-N = likely negative; VL-N = very likely negative; ML-N = most likely negative; P-P possibly positive; L-P = likely positive; VL-P = very likely positive.

6.3.4 Summary of Results

Comparisons of pre- and post-match NMRT measures showed significant differences in Ct, Ft, and RelStiff for all player-sessions. Pre- to post-match comparisons within independent variable groups showed consistent decreases in RelStiff, though significant differences in Ft and Ct time varied. From Year 2 and Mat 2 groups, a significant pre- to post-match decrease in CMJ was observed. Comparison of NMRT measures between independent variable groups found significant differences in CMJ and RelStiff measures for substitution status, with higher CMJ and RelStiff for FULL compared to SUB player-sessions. For chronological age groups, CMJ height was observed to be significantly greater in Year 2 compared to Year 1. The Year 1 group had significantly longer Ct, longer Ft ($p = 0.002$) and higher RelStiff ($p = 0.007$) compared to Year 2. A significant main effect for maturation status was also observed for CMJ height, with higher CMJ height observed for Mat 2 compared to Mat 1. A significant interaction was found with Mat 2 decreasing CMJ pre- to post-match and Mat 1 increasing CMJ from pre- to post-match, also shown in significant differences in rates of change between maturation groups.

Analysis of the relationships between CMJ, RSI, and RelStiff differences did not reveal significant correlations with the exception of small negative correlations between the change in CMJ and relative DECEL in all cases and within the full-match sub-group, though this significant correlation was absent within the substitute sub-group. Inferential statistics for CMJ and RSI demonstrated varied responses per match per team with wide confidence intervals suggesting large between-participant differences in responses. In some instances, per match per team results indicated overall positive changes in neuromuscular response. For RelStiff measures, responses for both teams per match were frequently negative.

6.4 Discussion

The current study is the first to examine the neuromuscular response of adolescent female soccer players to match-play using field-based exercise tests. Data demonstrate decreases in RelStiff may occur regardless of substitution status, position, chronological age, or maturation status. A negative correlation between changes in CMJ and DECEL in match load shows a negative neuromuscular response is related to higher numbers of deceleration, particularly in FULL conditions. The current data also provide information for coaches and support staff on the chronological age and maturation effects on NMRT measures that should be considered when evaluating neuromuscular response to match-play in adolescent female soccer.

6.4.1 The effect of substitution status on neuromuscular response

It is interesting to note the significant main effect between FULL and SUB conditions for CMJ and RelStiff measures, with FULL player-sessions having comparatively higher CMJ and RelStiff measures including significantly higher pre-match CMJ. In a majority of cases, players did not know if they would be substitutes or not prior to pre-match testing as coaches for both teams announced starting players and substitutes after pre-match testing and, due to unlimited substitution rules, starting players frequently did not complete an entire match. Additionally, these between-group differences were preserved in post-match testing and no significant differences were observed for rates of change between FULL and SUB conditions. This suggests that players selected or expected by coaches to play entire matches may have greater lower limb power as shown in higher CMJ heights and higher relative leg stiffness which is related to increased running speed and decreased energy cost of running (Butler et al., 2003), indicative of higher match performance potential.

In contrast to findings in Chapter 5 where substitution use appeared to mitigate between-half match performance decrements for Forward and Defender players, differences between FULL and SUB rates of change in neuromuscular response were not significant and there were no significant interactions for position and substitution status. However, it may be of note that FULL player-sessions were observed to have significant pre- to post-match increases in Ct and decreases in Ft and that this was not observed in SUB player-sessions, although these significant differences were not observed to affect rates of change, with no significant differences of RelStiff rates of change observed between substitution conditions. Further, when controlling for time played in comparisons of FULL and SUB conditions, time played did not have a significant effect on the rates of change for any NMRT measure.

Specifically, deceleration as well as acceleration efforts have greater energy costs than constant running (di Prampero, 2005; Osgnach et al., 2010) and have been linked to decreased neuromuscular performance (Nedelec et al., 2014) as reflected in negative correlations of CMJ responses and relDECEL counts. Consideration of deceleration counts per match combined with monitoring neuromuscular response via CMJ may provide practitioners with important information about the fatiguing effects of match-play on individual players in adolescent female soccer.

6.4.2 The effect of position on neuromuscular response

In examining match loads per position in Chapter 5, positional differences were evident with Forward players completing more sprint-speed distances and Midfield players completing more total distances compared to the other positions. In the current chapter, all positional groups including Mix were observed to have significant pre- to post-match decreases in RelStiff. Some positional differences were observed in neuromuscular response measures, with significantly increased Ct in both Forward and Defender player-sessions. Rates of change in pre- to post-match measures of RelStiff show Forward player-sessions with the highest mean rate of change (Δ RelStiff = -6.86 ± 8.71) and Midfield player-sessions with the lowest rate of change (Δ RelStiff = -4.63 ± 8.18), which may be related to observed positional differences in match load where Forward players were observed to complete more sprint-speed running, however positional differences for rates of change were not significant.

6.4.3 CMJ height measures – effects of maturation and chronological age

Comparison of chronological age groups showed the older Year 2 age group had significantly higher overall CMJ height. This aligns with previous research showing CMJ performance in female soccer players increases with age until 15 – 16 years (Vescovi et al., 2011). As players in the current study are under 16 years of age with chronological age groups Year 1 and Year 2 corresponding to 14 and 15 years, respectively, a difference in CMJ height between age groups may be expected and is further reflected in the significant difference in CMJ height between maturation groups with higher CMJ height for Mat 2 (post-PHV >2.5 years) compared to Mat 1. Limited information is available on the effects of maturation on CMJ height or lower limb strength in post-pubertal female athletes (De Ste Croix et al., 2003) as compared to chronological age. One study assessing the effect of maturation on CMJ height in different age groups within an RTC observed an increase from 1.5 years post-PHV (28.63 cm) to 2.5 years post-PHV (33.42 cm) that was considered *most likely* to be an increase using inferential statistics (Emmonds et al., 2018). Comparatively, CMJ in the current study was lower based on maturational offset with Mat 1 (<2.5 years post-PHV) performing 26.14 cm and Mat 2 (>2.5 years post-PHV) performing 28.74 cm, although current study measures were taken on a match day compared to a physical characteristic assessment under controlled conditions in Emmonds et al (2018) which may affect results. In further consideration of chronological age and the occurrence of a plateau from around 15 – 16 years of age (Vescovi et al., 2011), CMJ height in the current study was slightly lower compared to CMJ testing of similarly aged national teams (national U17: 29.0 cm; national U15: 28.3. cm v U16 current study CMJ: 27.0 cm) (Castagna & Castellini, 2013; Datson, 2016) which may reflect the different age groups in the current study as well as a non-international performance standard. Similar CMJ height was also observed in a longitudinal study including adolescent female soccer players under 18 years of age, with 27.9 ± 3.1 cm (Hauger et al., 2012), which is comparable to present data. These comparisons suggest the CMJ results in the present study are appropriate measures of CMJ height for the chronological age groups involved in the current study. However, coaches, including performance and strength and conditioning coaches, should be aware of possible chronological and maturation effects on CMJ measures.

6.4.4 CMJ response to match-play

A significant difference was observed for pre- to post-match changes in CMJ height for the Year 2 group, but not Year 1, with a non-significant small increase in CMJ height for Year 1, but a significant decrease in CMJ for Year 2. Similarly, Mat 1 players were observed to have a non-significant tendency of a small increase in CMJ height from pre- to post-match, whereas a significant pre- to post-match decrease in CMJ height was found for the Mat 2 group, reflected in a significant interaction effect for maturation in CMJ. A comparison of relative match loads between chronological age groups and between maturation groups (Appendix 6.2) did not reveal significant between-group match loads, suggesting differences in CMJ response are not related to heightened match intensity or high-speed activity for older or more mature players. The significant negative response in CMJ height observed for the older Year 2 group and the higher maturation status Mat 2 group aligns with previous research in adult female soccer, which observed significant decrements in CMJ height from pre- to post-match (Andersson et al., 2008), however, this is not the case for the Year 1 and Mat 1 findings of non-significant increase. Observation of a positive change in CMJ height in the Year 1 group and Mat 1 group where a negative change may be expected in response to match-play is not unique. One study of CMJ response in U15 female soccer players (13.1 ± 1.4 years) observed increases in mean relative force production from CMJ tests after a 90-minute soccer match simulation (Wright et al., 2017). In the Wright et al (2017) study, session RPE measures steadily increased during the match simulation suggestion increased exertion, however, the neuromuscular response was instead a positive change in CMJ measures.

The U15 age group from Wright et al (2017) aligns with the Year 1 chronological age group in the current study where an increase in CMJ height from pre- to post-match was similarly observed, suggesting a potential age and maturation effect on CMJ response to match-play. Positive response in CMJ post-match is also likely due to a potentiation effect on lower limb musculature in response to match-play, possibly related to increased motor neuron excitability, motor unit recruitment, or activation of synergists (De Ste Croix et al., 2015;

Deutsch & Lloyd, 2008). A previous study of CMJ response in endurance runners to incremental exhaustive exercise found that 12 of 22 athletes had positive CMJ responses post-exercise due to post-activation potentiation, which allowed for maintenance of peak force production for CMJ and subsequent increase in CMJ performance (Boullosa et al., 2011). Fatigued players may also use compensatory mechanisms to maintain CMJ height (Bonnard et al., 1994). A greater understanding of the effects of age, maturation, and post-activation potentiation on CMJ and lower limb strength in post-pubertal female soccer players is needed, and coaches and practitioners should be aware of the potential effects of maturation and chronological age on CMJ tests. In light of the current findings, further understanding of compensatory mechanisms resulting in increased or maintained CMJ height from pre- to post-match is necessary. Importantly, significant pre- to post-match decreases in CMJ height in Year 2 and Mat 2 groups and in individual responses represent a negative neuromuscular response to match-play. Decreased lower muscle power demonstrated by decreased CMJ height suggest altered neuromuscular control about the knee, which represents an increased injury risk and is indicative of the presence of fatigue (Hewett et al., 2006; Knicker et al., 2011) in response to match-play.

Additionally, varied CMJ responses per team per match were also noted, particularly for Team B, with average team results assessed as negative in some matches and positive for others using magnitude-based inference. This aligns with varied CMJ responses to match-play that have been noted elsewhere in the literature. A study of a single female NCAA match including use of substitute players found no negative change in CMJ measures post-match (Hoffman et al., 2003). Another study of high-level domestic female players evaluated CMJ height one match and similarly found no significant difference from pre- to post-match (Krustrup et al., 2010). By comparison, a study of CMJ height measures pre- and post-match in two matches between high-level domestic female teams found average team decreases in CMJ height pre- to post-match in both matches (H. Andersson et al., 2008). In contrast, the present study evaluated CMJ response for several matches within the same season and found varied responses from match to match. The reasons for these match-to-match differences in CMJ response are unclear, though may be related to match-to-match variation, as high-intensity movement may be subject to higher variations between matches (Trewin et al., 2018a). In particular, eccentric contractions involved in running and deceleration are associated with muscle damage (Proske & Morgan, 2001) and creatine kinase (CK), a marker of muscle damage, has been shown to be significantly elevated as a result of match-play in female adolescent soccer players (Hughes et al., 2018). Further, CK and CMJ responses to match-play have been shown to be correlated (Hagstrom & Shorter, 2018; Russell et al., 2015). With potential between-match variations in high-intensity movements that induce muscle damage and fatigue, CMJ responses may also vary. However, further research on the match-to-match variability of both match loads and neuromuscular responses to match-play using CMJ tests are required.

6.4.5 Measures of leg stiffness

A further finding in comparing chronological age groups is a significantly lower Ct, higher Ft, and subsequent higher RelStiff in the younger group of Year 1 player-sessions. Studies of leg stiffness in female adolescent athletes are limited. One study of leg stiffness and the effects of maturation in female adolescent athletes have shown increased lower limb stiffness from pre- to post-pubertal stages, however when measures were normalised for body mass, the difference between maturation groups was not seen (Ford et al., 2010). In one study utilising the same submaximal test as the present study for relative leg stiffness in 3 chronological age groups (U13, U15, and U17), RelStiff was higher in younger players (U13: 44.64 ± 5.5, U15: 46.39 ± 8.8) compared to older players (U17: 36.46 ± 6.6) (De Ste Croix et al., 2016). De Ste Croix et al (2016) suggest chronologically older players may have lower RelStiff due to the likelihood of being taller or heavier, as leg stiffness measures in the present study are calculated with a relative factor of body mass and leg length (McMahon & Cheng, 1990). However, comparison of Ct, Ft, and RelStiff between maturation status groups did not reveal significant differences, only chronological age groups which in the current study did not overlap. Coaches and practitioners should be aware of chronological age differences in assessing RelStiff in adolescent female soccer players and the effects of maturation on RelStiff should be examined further.

6.4.6 Relative leg stiffness response to match-play

In consideration of the chronological age differences in RelStiff with lower RelStiff for older players, the lack of significant differences between independent variable groups on the rates of change in RelStiff, and the significant pre- to post-match decreases observed in analysis of all player-sessions and within all independent variable groups, RelStiff appears to be a sensitive test to neuromuscular responses in match-play. In a majority of player-sessions (71.4%), RelStiff decreased from pre- to post-match and negative changes in RelStiff per team per match were also frequently observed. Decreases in leg stiffness are related to exercise-induced muscle damage and decreased stretch-reflex sensitivity (Komi, 2000), which may be expected after prolonged high-intensity intermittent exercise such as soccer match-play.

One pattern that may contribute to negative changes in RelStiff is a tendency for significant pre- to post-match differences in Ct, but less so in Ft, as observed in significant increases in Ct from pre- to post-match in analysis of all player-sessions, as well as in FULL, Forward and Defender, Year 2, and Mat 1 and 2 independent variable groups. Ft also significantly decreased for the FULL group of player-sessions which may indicate a larger response to FULL match-play compared to substitution condition. Increased contact time and/or decreased flight time would contribute to decreases in RelStiff measures. In one study of adolescent male soccer players, half of the 10 participants were observed to have an increase and the other half a decrease in leg stiffness in response to a soccer-specific exercise test (Oliver et al., 2014). The researchers suggest that decreases in leg stiffness may be due to a yielding action during the contact phase due to increased joint extension prior to ground contact (Horita et al., 1999). The yielding action is likely a result of impaired SSC after repeated SSC loading (Nicol et al., 2006) that would occur due to running and sprinting in match-play. Reductions in Ct and leg stiffness as observed in the current study in response to match-play suggests impairment of the SSC and negative changes in neuromuscular control in the lower limb (De Ste Croix et al., 2015), which indicate increased injury risk in response to fatigue from match-play.

Although decreases in RelStiff were significant when analysing all player-sessions and within all independent variable groups, as well as when considered within a team per match, some individual differences were observed to increase in RelStiff in response to match-play. This can also be seen where magnitude-based inferences found probabilities of change per team were unclear for certain matches for Team A and Team B both, showing some players per team maintained or increased relative leg stiffness. In one study of leg stiffness in adolescent female soccer players, responses to soccer-specific exercise were similarly individualised with some players increasing and other decreasing in leg stiffness, including half of U15 players increasing and half decreasing in RelStiff and all U17 players increasing in RelStiff post-exercise (De Ste Croix et al., 2015). Increases in leg stiffness might be due to a potentiated state in the neuromuscular system where neural control increases leg stiffness by modulating the short-latency reflex of the triceps surae in a positive way (Hobara, Kanosue, & Suzuki, 2007; Oliver et al., 2014), suggesting that players alter muscular patterns to maintain leg stiffness in the presence of fatigue which may be the case in increased leg stiffness seen in adolescent female soccer players post-exercise (De Ste Croix et al., 2016).

In one study of submaximal hopping tests in males and females before and after a gym-based fatiguing protocol, researchers found that vertical leg stiffness was maintained by muscle activation and joint movement shifting from knee-dominant strategies in the pre-fatigue test to ankle-dominant strategies in a fatigued state (Padua et al., 2006). A study of leg stiffness in female athletes have shown a strong relationship between medial gastrocnemius stiffness and SSC movement in hopping tasks (Pruyn et al., 2014), which suggests maintenance or increase of leg stiffness measures as in the present study may rely on gastrocnemius stiffness in a shift toward an ankle-dominant strategy during hopping. This is supported by the same study of leg stiffness activation patterns in males and females observed a reduction in hamstring activation and increased gastrocnemius activation in a fatigued state (Padua et al., 2006), along with maintained quadriceps activation in female participants (Padua et al., 2005, 2006). However, research suggests that co-activation of the quadriceps and gastrocnemius places strain on the ACL (De Ste Croix et al., 2016; Fleming et al., 2001) and that this ankle-dominant strategy as seen in fatigued-state hopping may reduce knee joint stability (Oliver et al., 2014; Padua et al., 2006). Together, these studies suggest that altered neuromuscular control to maintain leg stiffness may represent movement patterns that increase injury risk in female soccer players. Coaches and support staff assessing leg stiffness in adolescent female soccer players should be aware of individual responses to match-play and the increased injury risk that alterations in leg stiffness may represent.

6.4.7 Reactive Strength Index

In comparison to CMJ and RelStiff measures, RSI was not observed to be significantly different between any independent variable group and was not significantly different in all player-sessions from pre- to post-match or within any independent variable group. Inferential statistics per match were similarly ambiguous, with the majority of RSI measures per team per match rated as *unclear* due to wide confidence intervals representing varied individual responses in maximal hop tests for RSI. In one study monitoring a 7-week in-season mesocycle in male youth rugby, RSI measures demonstrated large individual variability and inconsistent team responses to match-play (Oliver et al., 2015), similar to findings in the current study. A recent study evaluating the reactive strength index found that athletes could achieve similar RSI scores through different performance strategies (Healy et al., 2018): two athletes achieved nearly identical RSI scores, however, one athlete did so with an 18.1% shorter Ct and 17.4% lower jump height compared to the second athlete, despite researcher prompts to minimise Ct and maximise jump height. Healy et al (2018) note that these differences in performance strategy require different physical capacities where the athlete with a shorter Ct appears to have greater ability to tolerate a high stretch load and the second athlete has greater ability to produce an impulse for higher jump height. Although similar prompts for RSI testing were used in the current study, the lack of significant results or pattern of increased or decreased RSI response suggests different performance strategies may have been utilised per player, which may limit the usefulness of the maximal hop test for RSI in adolescent female soccer players. Healy et al (2018) suggest controlling for Ct to mitigate the use of differing performance strategies to improve testing, limiting the test to assess changes in the SSC. Future research is needed to assess the usefulness of the maximal hop test for RSI in adolescent female soccer players along with the inclusion of limitation of Ct during the test.

6.4.8 Neuromuscular responses and match load variables

Correlations assessing the effects of match load variables described in Chapter 5 on neuromuscular responses only demonstrated significant effects with small, negative correlations between pre- to post-match CMJ changes and relDECEL. This suggests a negative effect of higher DECEL on neuromuscular response. When assessed in FULL and SUB sub-groups, the small, negative correlation was noted in FULL but not in SUB conditions. This may be due to the higher total DECEL count for FULL compared to SUB conditions: FULL match observations had a mean of 264 – 271 deceleration counts (Table 5.5) where SUB match observations had a mean of 177 – 243 deceleration counts (Table 5.10). As fatigue onset is directly related to the specific task performed with intensity and muscle group involvement (Hunter et al., 2004; Waldron & Highton, 2014), cumulative eccentric loading from repeated deceleration which involves may alter neuromuscular control about the knee (Lakomy & Haydon, 2004) as decelerations are eccentrically performed by the quadriceps (Hewit et al., 2011). This result is indicative of the presence of fatigue in some player-sessions, representing potential increased injury risk (Hewett et al., 2006; Knicker et al., 2011). This also parallels the finding in Chapter 5 (5.5.2 Differences in 1st and 2nd half match loads for full-match conditions) of decreased DECEL counts in full-match players suggesting DECEL counts may be more a sensitive measure of fatigue onset within match play. The finding in the current study further highlights the importance of assessing low-speed, high-intensity movement such as accelerations and decelerations in female soccer.

6.4.9 Limitations

Some limitations are noted in the current study. The current battery of field-based tests utilised do not include force-time data, which is an acknowledged limitation, however, the tests used have been validated and shown to be reliable measures of neuromuscular response (Claudino et al., 2017; Lloyd et al., 2009) and provide an economical and mobile means to test neuromuscular response in ecologically valid settings of match-play. Maturation groups were arbitrarily chosen based on the current participant group that was generally within 2 years post-PHV. The mean maturational offset of 2.3 years was considered as a demarcation; however, this might not represent the mean maturational offset of the larger U16 population of RTCs and maturational groups and chronological age groups would similarly not overlap in the current group of participants. Match-to-match variability in neuromuscular response and the effects of match difficulty were also not accounted for and require further study.

It was also noted that there were no non-contact injuries that occurred during the observed matches, limiting concurrent consideration of in-match injuries and injury risk within the study data. Official injury data for the participants were not available. Observations in the current study were limited to matches only with a focus on post-match fatigue. Match observations were conducted during regular in-season matches avoiding pre-season and post-winter break periods where rapid increases in training occur after periods of no training or matches. Changes in training load, namely rapid increases and high cumulative training load, increase risk of injury such as non-contact ACL injuries (Jones et al., 2017), however the current study did not consider training load which is an acknowledged limitation.

6.5 Summary

The current study presents new data on the neuromuscular responses of adolescent female soccer players to match-play. Overall, pre- to post-match measures from the submaximal hop test of Ct, Ft, and RelStiff were found to be significantly different resulting in decreased RelStiff. Instances of increased RelStiff in response to match-play were observed, including in assessments of neuromuscular responses per match per team. CMJ measures were different between substitution groups, chronological age groups, and maturation groups with the FULL condition, older age group, and more mature group, respectively observed to have higher CMJ height. Further, pre- to post-match CMJ height changes showed significant decreases for both the Year 2 and Mat 2 groups, but this was not observed with the Year 1 and Mat 1 groups. These maturational and chronological differences should be noted by coaches and practitioners when evaluating CMJ in adolescent female soccer players.

A significant negative correlation was observed between the NMR measure of CMJ and relDECEL, particularly in full-match conditions, presenting a link between repeated eccentric movement during match-play and negative neuromuscular response. This highlights the importance of including low-speed, high-intensity movement in analysis of match-play. Associations of neuromuscular response with relSPR or relHSA were not found. The data suggest that both CMJ and submaximal hop tests for RelStiff may be useful in evaluating player responses to match-play. The maximal hop test for RSI demonstrated large variations in individual responses, suggesting it may not be a useful test to assess neuromuscular response in the current population. Individual differences were observed for RelStiff and CMJ which may reflect a potentiation effect due to match-play. Increased RelStiff may represent a change in change to an ankle-dominant strategy to maintain stiffness that could represent increased risk of knee injury and should be considered in addition to decreased RelStiff. Further, decreased CMJ height and decreased RelStiff indicate the presence of fatigue in response to match-play, representing an increased injury risk in adolescent female soccer players and may be used to monitor player response to match-play.

CHAPTER 7

Summary, Discussion, and Recommendations

7.1 General summary and practical implications of findings

This thesis is the first study to assess the match loads of substitutes in adolescent female soccer in relation to unlimited substitutions specific to youth soccer. The thesis enhances knowledge of match loads in adolescent female soccer per position, with consideration to high-speed and high-intensity efforts, including sprint-speed movement, accelerations, and decelerations. It additionally provides indications of fatigue development in response to match-play through tests of neuromuscular response in match settings, which for adolescent female soccer players have previously been limited to simulated match conditions. Further, it establishes the use of adult-based sprint-speed threshold for motion analysis for female soccer players ≥14 years of age based on maximal sprint speed tests. This work provides new and important information regarding the match loads of substitutes and the development of neuromuscular fatigue in response to match-play which is related to increased risk of injury present in fatigued states in adolescent female soccer players.

The aims of the thesis as outlined in Chapter 1 were to investigate sprint-speed ability in adolescent female soccer players in relation to a sprint-speed threshold for use in match load analysis; to investigate match loads in full-match and substitute match-play in adolescent female soccer with regards to high-speed and high-intensity movement; and to examine neuromuscular responses to match-play in adolescent female soccer players in light of substitution use and the potential impact of high-intensity movement on neuromuscular response.

The aim of Study 1 (Chapter 4) of this thesis was to determine the appropriateness of utilising an adult female sprint-speed threshold for U16 female players (research objective 1).

Using timing gates and a flying sprint to assess maximal sprint speed (MSS), MSS for adolescent female soccer players was shown to be 6.96 $m \cdot s^{-1}$. With methods proposed by Bradley and Vescovi (2015) to utilise 80 – 85% of tested MSS as the sprint-speed threshold, this yields a sprint-speed threshold of 5.57 – 5.92 $m \cdot s^{-1}$. This sprint-speed threshold for U16 players aligns closely with the sprint-speed threshold of 5.56 $m \cdot s^{-1}$ previously used in other studies to assess match load in adolescent female soccer (Ramos et al., 2019; Vescovi, 2014), demonstrating that the previously recommended sprint-speed threshold (Bradley & Vescovi, 2015) would not underestimate sprinting movement in U16 match-play and may be utilised in motion analysis with female players ≥14 years of age. Secondary findings and recommendations from the study include confirming the recommended use of a longer sprint distance >30 m to assess MSS (Bradley & Vescovi, 2015) compared to shorter match-specific sprint distance of ≤20 m. A 10 m flying sprint from a short sprint distance test provides an indication of match-specific sprint speed and can be used to assess match-specific speed performance. Sprint tests for both distances were found to be reliable using GPS, with the mean of 3 trials providing a stronger test for monitoring sprint speed over time.

The aims of Study 2 (Chapter 5) of this thesis were to investigate match loads in adolescent female soccer (research objective 2) and to explore differences between substitute and full-match player match loads (research objective 4). Position-specific match loads observed in the study were similar to positional match load patterns observed in female soccer (Andersson et al., 2010; Datson et al., 2017; Gabbett & Mulvey, 2008; Hewitt et al., 2014; Vescovi, 2014), with Midfield players covering greater total distances and having higher work rates, and with Forward players completing longer SPR distances and generally larger proportions of total distance in high-speed activity zones (SPR and HSR). These patterns were also seen in substitute conditions, with higher WR in Midfield players and higher relative SPR distances in Forward players. In comparing full-match and substitute conditions within-position, relative match load for Forward players was not significantly different between substitution and full-match conditions. However, significant differences were observed between conditions for Midfield and Defender players with higher work rates, relative HSR, relative ACCEL, and relative DECEL observed in substitute conditions. Importantly, although time played is less for substitutes, observed match loads demonstrate a higher intensity in the substitution condition for Midfield and Defender players. Coaches and support staff should be aware of these differences between positions and substitution conditions. These differences may inform training programming specific to positions and substitutes, where Forward players may focus on sprint-speed development and distances and Midfield players may focus on aerobic capacity for longer total distances during match-play. With higher work rates noted in substitution conditions, training may incorporate additional high work rate periods to prepare players for substitution match-play.

In considering 1st to 2nd half match load changes which may provide an indication of fatigue onset within match-play, observations in Study 2 did not align with previous research in both adult and adolescent female soccer: previous studies describe a decrease in high-speed activity (HSA) distances from 1st to 2nd half (Andersson et al., 2010; Datson et al., 2017; Mara et al., 2017a; Ramos et al., 2017; Vescovi, 2014), however this study did not generally observe decreases in HSA distances for full-match players. Instead, decreases in total distance were the result of decreases in LOW distances, with SPR distances observed to be similar between match halves. This coincided with decreases in AVG speed and average HR, suggesting players incorporated more time at standstill in the 2nd half. Instead, between-half decreases in deceleration counts for all positions as well as decreases in acceleration counts for Midfield and Defender players demonstrate some decreases in high-intensity movement within match-play do occur, indicating that low-speed but high-intensity movements such as accelerations and decelerations may provide a more reliable indication of fatigue onset in match-play. Further, in considering between-half differences in substitution conditions, patterns of decreased match load as seen in full-match conditions were not observed in Forward and Defender substitutes. However, between-half differences were present in Midfield substitutes despite frequent Midfield substitutions, although an effect of extended rest (SUBrest) was observed to mitigate significant decreases in relative ACCEL and relative DECEL counts. Of note is that substitutions for Forward and Defender players and extended rest periods for Midfield substitutes were observed to mitigate decreases in match load compared to full-match players. These findings may impact on decisions coaches make in utilising substitutions in order to mitigate declining performance into later match stages, as well as for consideration in player development in preparing players for matches with limited substitutions, and for support staff in monitoring performance decrements during match-play.

The aims of Study 3 (Chapter 6) were to examine the effects of high-speed movement, accelerations, and decelerations on neuromuscular response (research objective 3), and to explore differences in neuromuscular response between substitutes and full-match conditions (research objective 4). Comparing results of exercise performance tests from pre- to post-match, relative leg stiffness was observed to significantly decrease. Significant decreases were observed overall and in all independent variable groups. Magnitude-based inferences per team per match also revealed frequent negative responses of relative leg stiffness. Additionally, some individual differences were noted, with positive responses of relative leg stiffness; while positive changes denote an increase in relative leg stiffness, this change in measure may reflect a movement strategy to maintain leg stiffness that indicates higher injury risk in a fatigued state. In examining the relationship of match load to leg stiffness responses, no significant relationships with high-speed or high-intensity movement were observed. In general, coaches and support staff may utilise submaximal hop tests to assess changes in neuromuscular response to match-play. Changes in relative leg stiffness represent altered neuromuscular control of the lower limb and increased risk of injury which coaches and support staff should be aware of in implementation of recovery strategies.

In examining the relationship of match load to CMJ responses, a negative correlation between CMJ response and relative DECEL was observed demonstrating negative neuromuscular responses are related to higher deceleration counts. In assessing sub-groups for substitution and full-match conditions, this relationship was present in full-match but absent in substitution conditions suggesting higher total deceleration counts due to full-match participation may have greater impact on negative CMJ responses. Relative SPR, relative HSA distances, and relative ACCEL were not found to be associated with changes in neuromuscular response. Further findings include a maturation and a chronological effect on CMJ height rates of change from pre- to post-match, with older and more mature players observed to have significant pre- to post-match decreases in CMJ height compared to younger and less mature players observed to maintain CMJ height. Additionally, in contrast to findings in Chapter 5 where the substitution condition mitigated significant decreases in match load for Forward and Defender players, no significant effects were observed for combined substitution status and position on neuromuscular responses to match-play. Further, magnitude-based inferences for per team per match analysis showed individual variations in neuromuscular response in the CMJ test, with some per team per match instances of positive CMJ response. Positive CMJ response per team to match-play has been observed in NCAA soccer where substitution rules are similar to youth (Hoffman et al., 2003) and in U15 adolescent female soccer in response to simulated match-play (Wright et al., 2017). Positive CMJ response may be due to a post-activation potentiation effect which allows for maintenance of peak force production and increase in CMJ response (Boullosa et al., 2011). This may be related to increased motor neuron excitability, motor unit recruitment, or activation of synergists (De Ste Croix et al., 2015; Deutsch & Lloyd, 2008). However, the observed maturation and chronological age effect and individual neuromuscular responses warrant further investigation. Coaches and support staff for teams should be aware of these differences in maturation and chronological age groups and individual differences in CMJ responses, in addition to the indication of negative changes to neuromuscular response represented by decreased CMJ height in response to decelerations in match-play.

7.2 General Discussion

In Chapter 4 (Study 1), maximal sprint speed in a group of U16 participants was examined in relation to a sprint-speed threshold for use in motion analysis based on recommendations for female soccer speed thresholds (Bradley & Vescovi, 2015). Considering that youth soccer players utilise high percentages of their individual MSS during match-play (Mendez-Villanueva et al., 2011), assessing sprint-speed ability in players is useful to determining when sprint-speed efforts occur in match-play and suggests that the use of assessed sprint speed to determine sprint-speed thresholds for match-play is both logical and ecologically valid (Datson, 2016; Mendez-Villanueva et al., 2011). Data from Study 1 showed sprint speeds for high-level U16 female players were comparable to assessed sprint speeds in similar adolescent-aged cohorts (Datson, 2016) and other U16 RTC players in England (Emmonds et al., 2020). The data presented in this thesis adds further knowledge to the sprint-speed abilities of high-level female adolescent players and, alongside comparable sprint speeds assessed in other studies (Datson, 2016; Emmonds et al., 2020), suggests the sprint-speed threshold used in previous studies of adolescent female match loads (Ramos et al., 2019; Vescovi, 2014) can be appropriately applied to female soccer match-play for ≥14 years of age.

Although U16 adolescent female soccer players were observed to be capable of sprinting at speeds to justify use of sprint-speed thresholds previously used to analyse female adolescent soccer match-play (Ramos et al., 2019; Vescovi, 2014), large individual differences in utilisation of sprint-speed ability during match-play were observed in match analysis, with few sprint-speed efforts (SSE) observed in some full-match observations in Chapter 5 (Study 2). While high-speed activity during match-play is important to match performance (Krustrup et al., 2005; Ramos et al., 2019), data in the current study show sprint-speed ability may be less frequently utilised in some instances, although this work did not seek to determine the cause of differences in sprint-speed utilisation or variability in adolescent female soccer. This may reflect match-to-match variation as observed with differences in high-speed activity between matches in adult female soccer match-play (Trewin et al., 2018a).

In addition to the importance of HSA to match performance, HSA has also been considered as a marker for fatigue onset within match-play (Andersson et al., 2010; Mohr et al., 2003, 2008). However, although sprint-speed distances from full-match conditions were similar to those in other studies of female adolescent match-play (Ramos et al., 2019; Vescovi, 2014), HSA was not observed to decrease between the 1st and 2nd halves in the current study (Chapter 5). This is not in agreement with previous studies which observed decreases in HSA into later match stages in adult female match-play (Andersson et al., 2010; Datson et al., 2017; Hewitt et al., 2014; Mara et al., 2017a; Mohr et al., 2008; Ramos et al., 2017; Strauss et al., 2019) and between halves in adolescent female match-play (Vescovi, 2014). Instead, data including decreased average speed and decreased average HR in the current study suggested that players spent more time at standstill during the 2nd half. This may be considered a pacing strategy to maintain high-speed ability as shown in the data, and to mitigate fatigue (Drust et al., 2007; Edwards & Noakes, 2009; Link & Weber, 2017; Trewin et al., 2018b). By contrast, ACCEL and DECEL counts were not observed to be significantly different between positions in full-match conditions, with decreases in DECEL between halves noted for all positions and decreases in ACCEL noted for Midfield and Defender players. Between-half decreases in ACCEL and DECEL counts observed in the current study — as high-intensity movements that may not reach sprint speed — may provide better indications of decreasing match performance, particularly in light of individual player differences in sprint-speed efforts and distances where some players may not frequently utilise sprint-speed ability. Additionally, the difference between the current study with a lack of observed decreases in HSA compared to other studies in female soccer underscores the need to additionally assess neuromuscular response to match-play in addition to match load.

In Chapter 6 (Study 3), neuromuscular responses were reported utilising three exercise performance tests. Statistical analysis of maximal hop test results for reactive strength index (RSI) did not show any significant differences from pre- to post-match overall nor in independent variable groups considered in the study. This brings into question the usefulness of RSI from the maximal hop test in female adolescent soccer players, though a recent study suggests contact time should be controlled for during the test to mitigate the use of different hopping strategies (Healy et al., 2018). By contrast, relative leg stiffness measures were significantly different from pre- to post-match overall and within each independent variable group, including per position and per substitution condition. Decreases in relative leg stiffness represent negative impairments of the stretch-shortening cycle (SSC) and negative changes to neuromuscular control of the lower limb (De Ste Croix et al., 2015) likely as a result of repeated SSC loading (Nicol et al., 2006) that would occur due to intermittent high-intensity activities in soccer. Individual neuromuscular responses of increased leg stiffness were also observed, however, these might be the result of changes to ankle-dominant strategy in hopping to maintain lower limb stiffness, which may indicate increased injury risk in a fatigued state (Oliver et al., 2014; Padua et al., 2006). Further biomechanical assessment of this hopping test in female adolescent soccer players in warranted to understand whether maintenance or increases in relative leg stiffness are due to changes in hopping strategy. Practitioners should be aware of the potential increased injury risk represented by positive and negative responses in submaximal hopping results and relative leg stiffness.

Where data in the current work demonstrated significant between-position differences in match load (Chapter 5) similar to those reported elsewhere in the literature (Andersson et al., 2010; Datson et al., 2017; Gabbett & Mulvey, 2008; Hewitt et al., 2014; Vescovi, 2014), positional differences were not found in neuromuscular responses to match-play. High-intensity movements results in repeated SSC loading or eccentric contractions from high-speed running and decelerations are thought to affect neuromuscular responses (Hewit et al., 2011; Nedelec et al., 2014; R. Thorpe & Sunderland, 2012; Williams, 1985). However, while positional differences for rates of change, with Forward players observed to haver higher rates of change in relative leg stiffness and Midfield players with the lowest, these positional differences were not significant.

By contrast, data showed some indications of differences between FULL and SUB conditions in neuromuscular responses (Chapter 6). For relative leg stiffness, measures of contact time and flight time to calculate leg stiffness were significantly increased and decreased from pre- to post-match, respectively, for full-match conditions, whereas this was not observed in substitution conditions. However, this did not impact on the rate of change as analysis did not reveal significant differences between substitution condition rates of change in RelStiff. Match load data (Chapter 5) revealed that substitution status resulted in mitigation of performance decrements between match halves for Forward and Defender players in addition to mitigation of performance decrements with extended rest in Midfield players, suggesting substitution status may mitigate fatigue onset during match-play. Neuromuscular response data suggest this may be the case for relative leg stiffness with significant increases in Ct and decreases in Ft in FULL conditions compared to SUB conditions, which possibly relates to less SSC loading due to less time played and lower total distances in substitution conditions. Additionally, higher total deceleration counts in full-match conditions (Chapter 5) may negatively impact CMJ response (Chapter 6). This is likely due to muscle damage incurred due to repetitive eccentric loading (Proske & Morgan, 2001) which may impact muscle force production (Raastad et al., 2003) that would be present in decreased CMJ height response. Additional research on the effects of match load and the relationship of change in match load variables within match-play to neuromuscular response is warranted. Changes in relative leg stiffness and negative changes to CMJ height indicate the development of neuromuscular fatigue in response to match-play and represent an increased risk of injury. Collectively, these findings provide important information to enhance the understanding of the effects of substitutions on match load and neuromuscular responses to match play, providing new and important information about the development of neuromuscular fatigue and increased injury risk in response to match-play in adolescent female soccer players.

7.3 Recommendations for future research

Several considerations for future research arose as a result of the current thesis. Although this thesis focused on sprint-speed ability in female adolescent soccer players (Chapter 4), additional research on maximal aerobic speed in adolescent players would be of further benefit to assessing high-speed running in match-play accurately. The concurrent examination of match load using individualised and fixed speed thresholds for motion analysis may also provide further information to enhance training programming in youth female soccer (Malone et al., 2017). Use of acceleration and deceleration (Chapter 5) also merit further investigation in regards to 1) utilising combined running speed and acceleration thresholds to categorise high-intensity movement (Mara et al., 2017b) and 2) utilising acceleration and deceleration to analyse match load as a potential tool for assessing fatigue onset. Further, larger data sets for female adolescent match-play gathered with similar methods could be established in future studies, which may enable speed thresholds to be determined using retroactive statistical analysis modelling methods (Park et al., 2018). Together, these recommendations suggest further examination and discussion on motion analysis methods and recommended speed thresholds for adolescent female soccer settings is warranted.

This thesis is the first to assess substitution match loads within adolescent female soccer (Chapter 5), however, further data on substitution match load is needed to provide comparative data on substitution match load, particularly in the context of unlimited substitution due to youth soccer rules. Further studies may include controlled time played for substitutes to mitigate the large differences in time played between substitutes that may occur due to unlimited substitution rules. Analyses of match load should include high-intensity movement analysis alongside traditional assessment of high-speed movement as an additional tool to track changes within match-play. Similarly, this thesis is also the first to report on neuromuscular response to soccer within the context of real match-play as opposed to controlled simulated match-play, though further data for comparative purposes in female adolescent soccer is needed. As previous studies of neuromuscular response to simulated match-play provided a basis for this thesis, this thesis may also provide a basis for further research into the neuromuscular responses of female adolescent soccer players to match-play. In particular, the relationship between high-intensity movement in decelerations and negative neuromuscular responses merits further investigation.

This work did not examine the match-to-match variability of match load across a season nor the impact of match factors such as win or loss record or goal differential on the match load or neuromuscular responses to match-play. Variability in match load may have some effect on the neuromuscular responses to match-play and should be considered in future studies. Finally, injury data was not tracked alongside neuromuscular responses and match load within the current work. As neuromuscular response provides an indication of increased injury risk due to the presence of fatigue, examination of the interaction between field-based measures of neuromuscular response and injury occurrence, particularly in the 2nd half of match-play, may provide further understanding of injury risk in female adolescent soccer.

CHAPTER 8

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CHAPTER 9

Appendices

Appendix 2.1

Hodun, M., Clarke, R., De Ste Croix, M. B. A., Hughes, J. D. (2016). Global Positioning System Analysis of Running Performance in Female Field Sports. *Strength and Conditioning Journal*, 38(2), 49-56. doi: 10.1519/SSC.0000000000000200

GPS in female field sports Hodun et al 2016.pdf

Appendix 3.1 Weather conditions per match

	Match	Temperature (˚C)	Weather description	Wind speed (km·hr^{-1})	Humidity %	Pitch type
Team A	Match 1	16	Partly sunny	16	54	Grass
	Match 2	8	Rain	18	99	Grass
	Match 3	18	Showers	27	93	Grass
	Match 4	10	Passing clouds	11	71	Grass
	Match 5	4	Partly sunny	20	83	Grass
	Match 6	9	Partly sunny	31	76	Grass
	Match 7	9	Overcast	12	66	Grass
	Match 8	10	Overcast	33	80	Grass
	Match 9	10	Partly sunny	14	71	Grass
Team B	Match 1	7	Passing clouds	13	82	3G
	Match 2	11	Drizzle, partly sunny	10	91	Grass
	Match 3	11	Light rain	15	96	Grass
	Match 4	12	Light rain	10	88	Grass
	Match 5	10	Mostly cloudy	28	92	Grass
	Match 6	15	Sunny	15	77	4G
	Match 7	11	Passing clouds	28	73	Grass
	Match 8	17	Sunny	3	68	Grass
	Match 9	18	Sunny	14	66	Grass
	Match 10	9	Scattered clouds	23	75	Grass
	Match 11	12	Passing clouds	13	81	Grass

Appendix 4.1 – Participant information letter and consent form for Study 1

Title of Study: Fatigue from sprinting in female youth football

UNIVERSITY OF GLOUCESTERSHIRE
at Cheltenham and Gloucester

Dear athlete and parent/guardian,

We are sport science researchers at the University of Gloucestershire. We would like to invite you to take part in a research project studying fatigue in female youth football. Below is some information regarding what participants will be asked to do as part of this project. Please read the information carefully.

What is the project about?

We are studying how fast youth female football players can run, how quickly they accelerate and decelerate when running, and how frequently high intensity motion occurs. Study findings will assist in identifying causes of fatigue and potential injury risk. As part of the study, we will also be assessing the use of Global Positioning System (GPS) devices.

About the study

This study is self-funded. All people involved have experience working with athletes/children and have completed a full DBS (formerly CRB) check. The study has been approved by the University Research Ethics Committee.

What risks are involved with participation and what will be done to minimise them?

The tests performed will follow strict, approved guidelines and do not involve any movement patterns or levels of exertion which differ from that which you would normally experience within a training session or match. All people involved have experience of the tests and using the equipment, and a full risk assessment has been completed and approved.

Who is taking part in the study?

The study involves U16 teams from the FA's Regional Training Centres and other regional academies.

What will I be asked to do?

Participants will have their height and weight measured, be fitted with a polyester harness over their training kit, and given a GPS device. After a standard warmup, participants will be asked to sprint the length of the football pitch and also to sprint 20 metres.

When will I do it?

Two testing sessions will occur during weekly training sessions one week apart.

Can I change my mind?

You can stop being a part of the study at any time. This will not affect your relationship with the University.

What will you do with the information?

We will store information collected on a secure computer and only the researchers will have access to the data. Once we have finished the study we will present the results at conferences and publish in an academic journal. Your name will never be used. It is important to know that your individual results may be passed on to your team management BUT only if you want this after you have seen the data, by completing the Data Consent Form below.

What if I have any questions or want to withdraw from the study?

If you have any questions or wish to stop participating and have all data removed from the study, please feel free to contact the principal investigator:

Megan Hodun, University of Gloucestershire, [redacted]

Supervisors: Prof. Mark de Ste Croix, University of Gloucestershire, [redacted] and Dr. Jonathan Hughes, University of Gloucestershire, [redacted]

What do I do next?

If you have read and understood everything that we want you to do and are happy to take part, please sign the consent form that is attached to this sheet.

Participant Informed Consent Form

I have had full details of the tests I am about to complete explained to me. I understand the risks and benefits involved, and that I am free to withdraw at any point. I confirm that I have completed a health questionnaire and I am in a fit condition to undertake the required exercise.

Participant Name: ____

Signed: ____ Date: _______________

Parent/Guardian Informed Consent Form

I have had full details of the tests my child is about to complete explained to me. I understand the risks and benefits involved, and that she is free to withdraw at any point.

Parent/Guardian Name: ____

Signed: ____ Date: _________

Data Consent Form

The data gathered in this study will not be passed on to any other party and will remain anonymous if you so wish. However, the data may be beneficial for you if passed on to the relevant members of your club. If you wish, your data can be shared with your team management after you have seen it, if you give permission by signing below:

Participant Name: ____

Signed: ____ Date: _______________

Appendix 5.1 – Participant information letter and consent form for Studies 2 and 3

Title of Study: Fatigue from sprinting in female youth football

Dear athlete and parent/guardian,

We are sport science researchers at the University of Gloucestershire. We would like to invite you to take part in a research project studying fatigue in female youth football. Below is some information regarding what participants will be asked to do as part of this project. Please read the information carefully.

What is the project about?

We are studying how fast youth female football players run, how quickly they accelerate and decelerate during matches and how often, how frequently high intensity motion occurs, and how these might affect neuromuscular fatigue. We are also studying how high intensity motion is affected by substitutions. Study findings will assist in identifying causes of fatigue and potential injury risk.

About the study

This study is self-funded. All people involved have experience working with athletes/children and have completed a full DBS (formerly CRB) check. The study has been approved by the University Research Ethics Committee.

What risks are involved with participation and what will be done to minimise them?

The tests performed will follow strict approved guidelines and do not involve any movement patterns or levels of exertion which differ from that which you would normally experience within a training session or match. All people involved have experience of the tests and using the equipment, and a full risk assessment has been completed and approved.

Who is taking part in the study?

The study involves U16 teams from the FA’s Regional Training Centres and other regional academies.

What will I be asked to do?

Participants will have their height and weight measured, be provided with a polyester harness to be put on by the participant in the confines of the changing room, and given a GPS device. After a standard warmup, participants will be tested to provide a neuromuscular baseline. These tests include jumping and hopping. Participants will then take part in their scheduled match. Neuromuscular tests will be repeated after the player has completed the match.

When will I do it?

Agreed matches during the 2018-2019 season.

Can I change my mind?

You can stop being a part of the study at any time. This will not affect your relationship with the University.

What will you do with the information?

We will store information collected on a secure computer and only the researchers will have access to the data. Once we have finished the study we will present the results at conferences and publish in an academic journal. Your name will never be used. It is important to know that your individual results may be passed on to your team management BUT only if you want this after you have seen the data, by completing the Data Consent Form below.

What if I have any questions or want to withdraw from the study?

If you have any questions or wish to stop participating and have all data removed from the study, please feel free to contact the principal investigator:

Megan Hodun, University of Gloucestershire, [redacted]

Supervisors: Prof. Mark de Ste Croix, University of Gloucestershire, [redacted] and Dr. Jonathan Hughes, University of Gloucestershire, [redacted]

What do I do next?

If you have read and understood everything that we want you to do and are happy to take part, please sign the consent form that is attached to this sheet.

Participant Informed Consent Form

I have had full details of the tests I am about to complete explained to me. I understand the risks and benefits involved, and that I am free to withdraw at any point. I confirm that I have completed a health questionnaire and I am in a fit condition to undertake the required exercise.

Participant Name: ____

Signed: ____ Date: _______________

Parent/Guardian Informed Consent Form

I have had full details of the tests my child is about to complete explained to me. I understand the risks and benefits involved, and that she is free to withdraw at any point.

Parent/Guardian Name: ____

Signed: ____ Date: _________

Data Consent Form

The data gathered in this study will not be passed on to any other party and will remain anonymous if you so wish. However, the data may be beneficial for you if passed on to the relevant members of your club. If you wish, your data can be shared with your team management after you have seen it, if you give permission by signing below:

Participant Name: ____

Signed: ____ Date: _______________

Appendix 6.1 Descriptive statistics for each NMRT measure, statistical significance of differences, and percent for greatest probable outcome per match

Team A

Match 1	n	Mean Δ	SD	±90% CI	p-value	Inferential outcome	% outcome probability
ΔCMJ	12	0.01	1.86	0.96	0.981	*Likely trivial*	78.5
ΔRSI							
ΔCt	12	5.3	17.9	9.3	0.331	*Possibly trivial*	51.1
ΔFt	12	-1.6	23.5	12.2	0.822	*Unclear*	
ΔRelStiff	12	-3.06	7.00	3.63	0.158	*Possibly negative*	74.5
Match 2							
ΔCMJ	10	-1.21	2.83	1.64	0.211	*Possibly negative*	70.5
ΔRSI	10	0.12	0.28	0.16	0.200	*Possibly positive*	73.1
ΔCt	10	4.0	15.8	9.2	0.448	*Possibly trivial*	59.5
ΔFt	10	2.1	15.3	8.9	0.679	*Unclear*	
ΔRelStiff	10	-2.08	7.25	4.20	0.388	*Unclear*	
Match 3							
ΔCMJ	9	-0.73	2.41	1.49	0.389	*Unclear*	
ΔRSI	9	-0.01	0.28	0.17	0.898	*Unclear*	
ΔCt	9	21.1	29.9	18.6	0.068	*Likely positive*	91.8
ΔFt	9	-21.6	22.4	13.9	0.020*	*Very likely negative*	96
ΔRelStiff	9	-7.24	9.57	5.93	0.053	*Likely negative*	94
Match 4							
ΔCMJ	11	0.39	1.24	0.68	0.327	*Likely trivial*	78.6
ΔRSI	11	0.03	0.47	0.26	0.843	*Unclear*	
ΔCt	11	2.6	15.7	8.6	0.590	*Unclear*	
ΔFt	11	-1.3	18.0	9.8	0.822	*Unclear*	
ΔRelStiff	11	-2.35	4.53	2.48	0.116	*Possibly negative*	68.4
Match 5							
ΔCMJ	10	-0.22	1.95	1.13	0.730	*Unclear*	
ΔRSI	10	-0.03	0.19	0.11	0.652	*Unclear*	
ΔCt	10	9.9	15.5	9.0	0.073	*Likely positive*	79
ΔFt	10	-10.9	17.9	10.4	0.088	*Likely negative*	75.8
ΔRelStiff	10	-4.34	5.12	2.97	0.025*	*Likely negative*	93.3
Match 6							
ΔCMJ	10	-0.57	1.60	0.92	0.292	*Possibly trivial*	59
ΔRSI	10	0.06	0.30	0.18	0.550	*Unclear*	
ΔCt	10	-5.4	21.6	12.5	0.451	*Unclear*	

ΔFt	10	6.4	49.4	28.6	0.693	*Unclear*	
ΔRelStiff	10	2.02	6.67	3.87	0.362	*Unclear*	
Match 7							
ΔCMJ	11	-0.22	1.95	1.07	0.717	*Unclear*	
ΔRSI	11	0.08	0.21	0.11	0.243	*Possibly positive*	57.5
ΔCt	11	11.2	18.0	9.8	0.067	*Likely positive*	
ΔFt	11	2.0	25.1	13.7	0.793	*Unclear*	
ΔRelStiff	11	-5.01	6.38	3.49	0.026*	*Likely negative*	94.3
Match 8							
ΔCMJ	9	-0.37	1.65	1.02	0.521	*Possibly trivial*	67.7
ΔRSI	9	-0.06	0.18	0.11	0.307	*Possibly negative*	49.6
ΔCt	9	3.5	13.9	8.6	0.472	*Possibly trivial*	64.1
ΔFt	9	-7.1	19.8	12.3	0.316	*Possibly negative*	52.1
ΔRelStiff	9	-2.80	6.87	4.26	0.256	*Possibly negative*	68.2
Match 9							
ΔCMJ	10	-0.04	2.57	1.49	0.966	*Unclear*	
ΔRSI	10	0.15	0.14	0.08	0.008*	*Very likely positive*	95.3
ΔCt	10	0.6	15.4	8.9	0.900	*Unclear*	
ΔFt	10	-5.1	8.0	4.6	0.074	*Possibly trivial*	73
ΔRelStiff	10	-1.68	6.30	3.65	0.420	*Unclear*	

Team B

Match 1	n	Mean Δ	SD	±90% CI	p-value	*Inferential outcome*	Percentage
ΔCMJ	13	-1.42	1.96	0.97	0.023*	*Likely negative*	89.4
ΔRSI	10	-0.16	0.42	0.25	0.263	*Unclear*	
ΔCt	13	-9.1	31.6	15.6	0.321	*Unclear*	
ΔFt	13	8.8	27.2	13.4	0.266	*Possibly positive*	60.6
ΔRelStiff	13	-14.80	8.63	4.27	<0.001*	*Most likely negative*	100
Match 2							
ΔCMJ	10	-0.48	1.64	0.95	0.376	*Possibly trivial*	63.9
ΔRSI	10	0.02	0.23	0.13	0.748	*Unclear*	
ΔCt	10	7.7	19.4	11.2	0.242	*Possibly positive*	61.9
ΔFt	10	-2.1	28.0	16.3	0.817	*Unclear*	
ΔRelStiff	10	-17.24	8.13	4.72	<0.001*	*Most likely negative*	100
Match 3							
ΔCMJ	15	-0.40	2.27	1.03	0.502	*Possibly trivial*	65.3
ΔRSI	15	0.04	0.27	0.12	0.557	*Unclear*	
ΔCt	15	-3.2	18.2	8.3	0.511	*Possibly trivial*	66.8
ΔFt	15	-1.3	27.8	12.7	0.863	*Unclear*	

ΔRelStiff	15	-13.09	4.24	1.93	<0.001*	*Most likely negative*	100
Match 4							
ΔCMJ	12	0.37	2.31	1.20	0.587	*Unclear*	
ΔRSI	12	0.09	0.31	0.16	0.342	*Unclear*	
ΔCt	12	3.1	21.6	11.2	0.626	*Unclear*	
ΔFt	12	15.9	32.6	16.9	0.120	*Likely positive*	82.4
ΔRelStiff	12	-3.14	7.57	3.92	0.179	*Possibly negative*	74.1
Match 5							
ΔCMJ	14	0.51	1.73	0.82	0.292	*Possibly trivial*	65.1
ΔRSI	14	-0.10	0.30	0.14	0.216	*Possibly negative*	67.8
ΔCt	14	9.0	23.8	11.3	0.178	*Possibly positive*	69.2
ΔFt	14	-6.3	27.9	13.2	0.416	*Unclear*	
ΔRelStiff	14	-3.08	6.91	3.27	0.119	*Likely negative*	76.9
Match 6							
ΔCMJ	11	-2.28	3.46	1.89	0.033*NP	*Likely negative*	94.1
ΔRSI	11	-0.10	0.54	0.30	0.545	*Unclear*	
ΔCt	11	13.8	18.0	9.8	0.029*	*Likely positive*	91.5
ΔFt	11	-26.1	24.7	13.5	0.006*	*Very likely negative*	98.7
ΔRelStiff	11	-4.85	8.23	4.50	0.079	*Likely negative*	88.5
Match 7							
ΔCMJ	9	-0.77	2.05	1.27	0.289	*Possibly negative*	53.9
ΔRSI	9	0.35	0.48	0.30	0.063	*Likely positive*	94.1
ΔCt	9	0.9	31.4	19.5	0.934	*Unclear*	
ΔFt	9	-3.9	33.0	20.5	0.735	*Unclear*	
ΔRelStiff	9	-4.83	7.97	4.94	0.106	*Likely negative*	86.5
Match 8							
ΔCMJ	7	0.23	3.52	2.59	0.871	*Unclear*	
ΔRSI	7	-0.002	0.32	0.24	0.985	*Unclear*	
ΔCt	6	9.8	26.0	21.4	0.397	*Unclear*	
ΔFt	6	-7.3	31.0	25.5	0.588	*Unclear*	
ΔRelStiff	6	-3.71	7.18	5.90	0.261	*Unclear*	
Match 9							
ΔCMJ	8	0.56	1.45	0.97	0.308	*Possibly trivial*	58.6
ΔRSI	5	-0.08	0.19	0.18	0.406	*Unclear*	
ΔCt	8	6.8	14.6	9.7	0.226	*Possibly positive*	57.9
ΔFt	8	-13.2	23.3	15.6	0.152	*Likely negative*	77.3
ΔRelStiff	8	-4.66	6.31	4.23	0.075	*Likely negative*	88.8

Match 10							
ΔCMJ	8	2.25	1.54	1.03	0.004*	*Very likely positive*	98.7
ΔRSI	8	-0.08	0.22	0.15	0.365	*Unclear*	
ΔCt	8	-2.4	17.7	11.8	0.718	*Unclear*	
ΔFt	8	-0.2	13.4	9.0	0.967	*Unclear*	
ΔRelStiff	8	-1.48	5.66	3.79	0.484	*Unclear*	
Match 11							
ΔCMJ	12	1.33	3.37	1.75	0.198	*Possibly positive*	73.4
ΔRSI	12	-0.02	0.20	0.10	0.780	*Unclear*	
ΔCt	12	7.0	22.1	11.5	0.297	*Possibly positive*	57.4
ΔFt	12	-7.2	16.0	8.3	0.150	*Possibly negative*	53.8
ΔRelStiff	12	-3.47	7.34	3.81	0.130	*Likely negative*	79.1

Appendix 6.2 Comparison of relative match loads between chronological age groups and between maturation groups

Comparison of mean (± SD) relative match load variables per chronological age

	n	WR (SD)	RelLOW (SD)	RelSPR (SD)	RelHIR (SD)	RelACCEL (SD)	RelDECEL (SD)
Year 1	117	103 (9.7)	93.4 (9.1)	2.1 (1.5)	9.6 (4.3)	3.8 (1.0)	3.8 (1.3)
Year 2	94	102.9 (12.1)	92.8 (10.5)	2.2 (1.4)	10.1 (4.3)	3.8 (1.1)	3.8 (1.2)
p-value		0.966	0.641	0.722	0.346	0.665	0.833

Comparison of mean (± SD) relative match load variables per maturation status

	n	WR (SD)	RelLOW (SD)	RelSPR (SD)	RelHIR (SD)	RelACCEL (SD)	RelDECEL (SD)
Mat 1	138	103.4 (10.6)	93.7 (9.7)	2.1 (1.5)	9.7 (4.3)	3.8 (1.0)	3.8 (1.3)
Mat 2	73	102.3 (11.3)	92.2 (9.6)	2.2 (1.6)	10.1 (4.3)	3.7 (1.1)	3.7 (1.2)
p-value		0.479	0.275	0.652	0.496	0.578	0.534

n = number of player-sessions; WR = work rate ($m \cdot min^{-1}$); relLOW = low-speed running distance (m) per minute played; relSPR = sprinting distance (m) per minute played; relHIR = high-intensity running distance (m) per minute played; relACCEL = number of accelerations per minute played; relDECEL = number of decelerations per minute played.