Northumbria Research Link

Citation: Fitzpatrick, John (2019) An individualised approach to monitoring and prescribing training in elite youth football players. Doctoral thesis, Northumbria University.

This version was downloaded from Northumbria Research Link: http://nrl.northumbria.ac.uk/id/eprint/42055/

Northumbria University has developed Northumbria Research Link (NRL) to enable users to access the University's research output. Copyright © and moral rights for items on NRL are retained by the individual author(s) and/or other copyright owners. Single copies of full items can be reproduced, displayed or performed, and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided the authors, title and full bibliographic details are given, as well as a hyperlink and/or URL to the original metadata page. The content must not be changed in any way. Full items must not be sold commercially in any format or medium without formal permission of the copyright holder. The full policy is available online: http://nrl.northumbria.ac.uk/policies.html

Northumbria University NEWCASTLE

UniversityLibrary

Northumbria Research Link

Citation: Fitzpatrick, John (2019) An individualised approach to monitoring and prescribing training in elite youth football players. Doctoral thesis, Northumbria University.

This version was downloaded from Northumbria Research Link: http://nrl.northumbria.ac.uk/id/eprint/42055/

Northumbria University has developed Northumbria Research Link (NRL) to enable users to access the University's research output. Copyright © and moral rights for items on NRL are retained by the individual author(s) and/or other copyright owners. Single copies of full items can be reproduced, displayed or performed, and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided the authors, title and full bibliographic details are given, as well as a hyperlink and/or URL to the original metadata page. The content must not be changed in any way. Full items must not be sold commercially in any format or medium without formal permission of the copyright holder. The full policy is available online: http://nrl.northumbria.ac.uk/policies.html

Northumbria University NEWCASTLE

UniversityLibrary

An Individualised Approach to Monitoring and Prescribing Training in Elite Youth Football Players

John F. Fitzpatrick

PhD

2019

An Individualised Approach to Monitoring and Prescribing Training in Elite Youth Football Players

John F. Fitzpatrick MSc, BSc (Hons)

A thesis submitted in partial fulfilment of the requirements of University of Northumbria at Newcastle for the degree of Doctor of Philosophy.

Research undertaken in the Faculty of Health and Life Sciences and in collaboration with Newcastle United Football Club.

October 2019

Abstract

The concept of how training load affects performance is founded in the notion that training contributes to two specific outcomes, these are developed simultaneously by repeated bouts of training and act in conflict of each other; fitness and fatigue (Banister *et al.*, 1975). The ability to understand these two components and how they interact with training load is commonly termed the "dose-response relationship" (Banister, 1991). The accurate quantification of training load, fitness and fatigue are therefore of paramount importance to coaches and practitioners looking to examine this relationship. In recent years, the advancement in technology has seen a rise in the number of methodologies used to assess training load and specific training outcomes. However, there is a general lack of evidence regarding the reliability, sensitivity and usefulness of these methods to help inform the training process. The aim of this thesis was therefore to improve the current understanding around the monitoring and prescription of training, with special reference to the relationship between training load, fitness and fatigue.

Chapter 4 of this thesis looked to establish test re-test reliability. Variables selected for investigation were measures of subjective wellness; fatigue, muscle soreness, sleep quality, stress levels and mood state, assessments of physical performance; countermovement jump (CMJ), squat jump (SJ) and drop jump (DJ) and the assessment of tri-axial accelerometer data; PlayerLoad^{TM} and individual component planes anterior-posterior (PL_{AP}), mediolateral (PL_{ML}), and vertical (PL_{V}), were collected during a sub-maximal shuttle run. The results from this investigation suggest that a short three minute sub-maximal shuttle run can be used as a reliable method to collect accelerometer data. Additionally, assessments of CMJ height, SJ height, DJ contact time (DJ-CT) and DJ reactive strength index (DJ-RSI) were all deemed to have good reliability. In contrast, this chapter highlighted the poor test re-test reliability of the subjective wellness

questionnaire. Importantly, the minimum detectable change (MDC) was also calculated for all measures within this study to provide an estimate of measurement error and a threshold for changes that can be considered ‘real’.

Chapter 5 assessed the sensitivity and reproducibility of these measures following a standardised training session. To assess sensitivity, the signal-to-noise (S: N) ratio was calculated by using the post training fatigue response (signal) and the MDC derived from Chapter 4 (noise). The fatigue response was considered reproducible if the S: N ratio was greater than one following two standardised training sessions. Three measures met the criteria to be considered both sensitive and reproducible; DJ-RSI, PL_{ML} and $\%PL_{V}$. All other measures did not meet the criteria. Subjective ratings of fatigue, muscle soreness and sleep quality did show a sensitive response on one occasion, however, this was not reproducible. This might be due to the categorical nature of the data, making detectable group changes hard to accomplish. The subjective wellness questionnaire was subsequently adapted to include three items; subjective fatigue, muscle soreness and sleep quality on a 10-point scale. The test re-test reliability of these three questions was established in Chapter 6, demonstrating that subjective fatigue and muscle soreness have good test re-test reliability.

Chapter 6 was comprised of two studies looking to simultaneously establish the dose-response relationship between training load, measures of fatigue (Part I) and measures of fitness (Part II). In Part I training load was strategically altered on three occasions during a standardised training session in a randomised crossover design. In Part II training and match load was monitored over a 6-week training period with maximal aerobic speed (MAS) assessed pre and post. A key objective for both studies was to assess differences in the training load-fitness-fatigue relationship when using various training load measures, in particular differences between arbitrary and individualised speed thresholds.

Results from Part I showed a *large* to *very large* relationship between training load and subjective fatigue, muscle soreness and DJ-RSI performance. No differences were found between arbitrary and individualised thresholds. In Part II however, individual external training load, assessed via time above MAS (t>MAS), showed a *very large* relationship with changes in aerobic fitness. This was in contrast to the *unclear* relationships with arbitrary thresholds. Taking the results from both studies into consideration it was concluded that t>MAS is a key measure of training load if the objective is to assess the relationship with both fitness and fatigue concurrently with one measure.

Chapter 7 subsequently looked to validate the training load-fitness-fatigue relationships established in Chapter 6 via an intervention study. The aim was to develop a novel intervention that prescribed t>MAS, in order to improve aerobic fitness, based on the findings from Chapter 6. Additionally, the fatigue response following a standardised training session was assessed pre and post intervention to evaluate the effect the predicted improvements in aerobic fitness would have on measures of fatigue. Results from Chapter 7 indicate a highly predictable improvement in aerobic fitness from the training load completed during the study, validating the use of t>MAS as a monitoring and intervention tool. Furthermore, this improvement in aerobic fitness attenuated the fatigue response following a standardised training session. The final key finding was the very strong relationship between improvements in aerobic fitness and reductions in fatigue response. This further highlights the relationship between t>MAS, fitness and fatigue.

In summary, this thesis has helped further current understanding on the monitoring and prescription of training load, with reference to fitness and fatigue. Firstly, a rigorous approach was used to identify fatigue monitoring measures that are reliable, sensitive and reproducible. Secondly, the relationship between training load, fatigue and fitness was clearly established. And finally, it has contributed new knowledge to the existing literature by establishing the efficacy of a novel MAS intervention to improve aerobic fitness and attenuate a fatigue response in elite youth football players.

Acknowledgments

Completing this programme of research in an applied environment has been extremely difficult at times, however, extremely rewarding in equal amounts. It has challenged me intellectually and emotionally to my limits, but has been an experience that will shape my future endeavours both professionally and personally. I would like to thank a number of people, without whom the completion of this thesis would not have been possible.

I would first like to thank my Principal Supervisor Dr Phil Hayes. I could not have completed this process without your continuous support and guidance. You have allowed me the flexibility to work at my own pace (often slower than we both would have liked!) and the freedom to fulfil my own research interests. Your expertise has helped me to develop as a researcher and practitioner and I hope we can continue to work together in the future.

I would also like to thank my second Supervisor Dr Kirsty Marie Hicks. I know it must have been difficult coming onto the team part way through the project however, your knowledge and expertise has helped immensely. I would particularly like to thank you for all your efforts in the final few months providing invaluable comments on my thesis.

I must also thank Professor Mark Russell. Your guidance through the initial stages of this research programme was instrumental in the outcome of the final thesis, thank you.

A number of colleagues have helped enormously throughout this programme of research. Craig Musham, Simon Tweddle and James Newton, you have all supported me throughout this process both professionally and personally. You have been my sounding boards throughout, and your assistance with data collection and other aspect of the project has been greatly appreciated.

I would also like to thank previous colleagues, Jack Ade, Richard Akenhead and Adam Rowan. Thank you all for your assistance and collaboration with various aspects of the project. Particularly Jack, although you left the club before the start of my PhD, your mentorship during the early stages of my career has helped to shape me into the researcher and practitioner I am today, thank you.

I am incredibly grateful to all the coaches, staff and players at Newcastle United Academy. Without your hard work and cooperation I would not have been able to complete this programme of research.

To my Mam and Dad, thank you both for everything you have done throughout my education and career. Without your help, support and encouragement the completion of this PhD, and my pursuit of a career in elite sport would not have been possible. I hope I have made you proud.

To Lauren, your support, patience and understanding throughout this process, particularly during the final write up has been incredible. Quite simply, I could not have done this without you. Finally, to Oliver, I thought your arrival four months ago could be the breaking of this project, however, it was the making of it. The thought of seeing you in the crowd on Graduation Day was the motivation I needed to get this thesis over the line. I dedicate this work to you.

Publications and Conference Proceedings

Peer Reviewed First Author Publications

Fitzpatrick, J. F., Hicks, K. M. and Hayes, P. R. (2018) Dose-response relationship between training load and changes in aerobic fitness in professional youth soccer players. *International. Journal of Sports Physiology and Performance*, 13(10), 1365-1370.

Fitzpatrick, J. F., Akenhead, R., Russell, M., Hicks, K. M. and Hayes, P. R. (2019) Sensitivity and reproducibility of a fatigue response in elite youth football players, *Science and Medicine in Football*, 3(3), 214-220.

Fitzpatrick, J. F., Russell, M., Hicks, K. M. and Hayes, P. R. (2019) The reliability of potential fatigue monitoring measures in elite youth soccer players. *The Journal of Strength and Conditioning Research*, Published ahead of print.

Related Peer Reviewed Publications

Ade, J., Fitzpatrick, J. F. and Bradley, P. S. (2016) High-intensity efforts in elite soccer matches and associated movement patterns, technical skills and tactical actions. Information for position-specific training drills. *Journal of Sports Sciences*, 34(24), 2205-2214.

Conference Communications

Fitzpatrick, J. F., Russell, M. and Hayes, P. R. (2016) Reliability of a fatigue response in elite youth football players. *21st annual Congress of the European College of Sport Science*, Vienna, Austria, 6th – 9th July 2016.

Fitzpatrick, J. F., Hicks, K. M. and Hayes, P. R. (2017) Dose-response relationship between training load and changes in aerobic fitness in elite youth soccer players. *5th World Conference on Science in Soccer*, Rennes, France, 31st May – 2nd June 2017.

Fitzpatrick, J. F., McLaren, S., Hicks, K. M. and Hayes, P. R. (2018) Dose-response relationship between training load and changes in fatigue in elite youth soccer players. *BASES Student Conference*, Newcastle, UK, 12th – 13th April 2018.

Fitzpatrick, J. F., Musham, C., Hicks, K. M. and Hayes, P. R. (2019). Relationship between changes in aerobic fitness and a training induced fatigue response in elite youth football players. *24th annual Congress of the European College of Sport Science*, Prague, Czech Republic, 3rd – 6th July 2019.

Table of Contents

List of Figures

Chapter 2

Chapter 3

Chapter 6

Chapter 7

Chapter 8

List of Tables

Chapter 6

Chapter 7

List of Abbreviations

The following abbreviations have been defined in the text in the first instance:

Abbreviation	Definition	Units
AD Load	Acceleration and deceleration load	± 2 $m \cdot s^{-2}$
AFL	Australian-Rules Football League	
ASR	Anaerobic speed reserve	
ATP	Adenosine triphosphate	
CK	Creatine kinase	
CMJ	Countermovement jump	
CV	Coefficient of variation	%
DJ	Drop jump	
DJ-CT	Drop jump contact time	Ms
DJ-H	Drop jump height	Cm
DJ-RSI	Drop jump reactive strength index	$m.s^{-2}$
ES	Effect size	
FT: CT	flight time: contraction time	
GPS	Global positioning system	
H^+	Hydrogen ions	
HDOP	Horizontal dilution of precision	
HR	Heart rate	
HRE	Heart rate exertion	
HR_{ex}	Exercise HR	
HR_{max}	Maximum heart rate	
HRV	Heart rate variability	
HSR	High speed running	> 17 $km.h^{-1}$
ICC	Interclass correlation	
iTRIMP	Individualised training impulse	
K^+	Potassium ions	
MAS	Maximal aerobic speed	$km.h^{-1}$
MBI	Magnitude based inference	
MDC	Minimum detectable change	
MEMS	Micro-electro-mechanical systems	

MPIC	Minimum practically important change	
MSS	Maximum sprint speed	$km.h^{-1}$
PCr	Phosphocreatine	
PL	PlayerLoad™	Arbitrary units
PL_{AP}	PlayerLoad™ anterior-posterior	Arbitrary units
PL_{ML}	PlayerLoad™ mediolateral	Arbitrary units
PL_{V}	PlayerLoad™ vertical	Arbitrary units
Pi	Inorganic phosphate	
RPE	Rating of perceived exertion	Arbitrary units
RS	Repeated sprint	
S: N	Signal-to-noise	
SD	Standard deviation	
SJ	Squat jump	cm
SPR	Sprint running	> 24 $km.h^{-1}$
sRPE	Session rating of perceived exertion	Arbitrary units
$s\dot{V}O_{2max}$	Speed at maximum oxygen uptake	$km.h^{-1}$
SSG	Small sided game	
t>MAS	Time above maximum aerobic speed	min
TD	Total distance	m
TE	Typical error	
TRIMP	Training impulse	
VHSR	Very high speed running	> 21 $km.h^{-1}$
$\dot{V}O_2$	Oxygen uptake	
$\dot{V}O_{2max}$	Maximum oxygen uptake	
Yo-Yo IR1	Yo-Yo Intermittent Recovery Level 1	
Α	Cronbach’s Alpha	
#sats	Number of satellites	

Declaration

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my own work. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others. The work was completed in collaboration with Newcastle United Football Club.

Any ethical clearance for the research presented in this thesis has been approved. Approval has been sought and granted by the Faculty Ethics Committee.

I declare that the word count of this thesis is 42, 653 words

Name: John F. Fitzpatrick

Signature:

Date: 21/10/2019

CHAPTER 1

1.0 INTRODUCTION

1.1 Introduction

The physical performance of football players competing in the English Premier League has significantly increased over recent years (Barnes *et al.*, 2014, Bush *et al.*, 2015). Elite players are required to compete in a high number of competitive matches including domestic, European and international games over the course of a 9-month season. Players will normally play weekly and often bi-weekly although, during periods of fixture congestion, players might play up to three matches in a 7-day period (Carling *et al.*, 2015). In order to succeed teams must possess players with both high levels of technical skill and well-developed physical capabilities (Bangsbo, 1994, Stølen *et al.*, 2005). The elite football player will typically cover around 9-13 km during a standard 90 minute match, depending on position. This distance includes high speed running (HSR), sprinting, jumping and tackling as well as accelerations, decelerations and physical contacts with the opposition (Mohr *et al.*, 2003, Rampinini *et al.*, 2007, Di Salvo *et al.*, 2009). The combination of a 90 minute game duration and the high-intensity intermittent nature of match play suggests that physiologically, elite players must have an excellent aerobic energy system in order to meet the endurance requirements of the game (Helgerud *et al.*, 2001, Impellizzeri *et al.*, 2006). Additionally, players must possess an excellent anaerobic energy system to perform repeated sprints, accelerations, changes of direction and maximal jumps (Buchheit *et al.*, 2010b, Akenhead *et al.*, 2013).

In modern elite football, the most popular way to assess the physical demands of training and match play is through global positioning systems (GPS) (Cummins *et al.*, 2013, Akenhead and Nassis, 2016). However, with these systems recording over 200 variables, clarity is required regarding which variables have a real impact on specific training outcomes (Drust, 2018). Impellizzeri *et al.* (2005) suggest that the training process is a combination of external load and individual characteristics that determine the specific training outcome. Early work by Banister *et al.* (1975), suggested that two simultaneous responses occur from a given training load; a positive function (fitness gain) and a negative function (fatigue). These two responses work in conflict with each other, it is therefore the balance between these two components that causes a shift towards a fatigued state or a fitness gain. This will ultimately determine the performance of an athlete. Very limited research has been completed to date looking to establish the relationship between training load, fitness (Akubat *et al.*, 2012, Manzi *et al.*, 2013) and fatigue (Thorpe *et al.*, 2015, Scott and Lovell, 2017) in football. With regards to fitness, only internal load measures and been used, suggesting an individualised training impulse (iTRIMP) has the strongest relationship with changes in aerobic fitness (Akubat *et al.*, 2012, Manzi *et al.*, 2013). No studies to date have assessed the relationship between external load and changes in fitness. With regards to fatigue, *small* to *large* relationships have been found between subjective ratings of fatigue and HSR (Thorpe *et al.*, 2015) and individualised external load (Scott and Lovell, 2017). However, methodological issues might be the cause of these small relationships. These studies will be discussed in greater depth in Chapter 2.

1.2 Aims and Objectives of the Thesis

The few studies that have established some association between training load, fitness and fatigue have failed to show any consensus on which measures are best for assessing training load; which measures are best used to monitor a player's level of fatigue or how these components interact to determine the physical performance of elite football players.

The overall aim of this thesis was therefore to further the current understanding around the monitoring and prescription of training, with special reference to the relationship between training load, fitness and fatigue in elite youth football players. This aim was addressed over the course of four experimental chapters, which set out to achieve the following objectives:

1. To determine the most appropriate methods for assessing fatigue in an applied environment by establishing the test-re-test reliability, sensitivity and reproducibility of potential fatigue monitoring measures. *(Chapters 4 and 5)*

2. To examine the dose-response relationship between training load, fitness and fatigue, with special reference to the use of individualised external training load. *(Chapter 6)*

3. To investigate the efficacy of a training intervention to improve aerobic fitness and subsequently examine its ability to attenuate a fatigue response. *(Chapter 7)*

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Introduction

The aim of this literature review is to provide background information regarding the monitoring of training load and fatigue in elite football players. The initial section of this review will look at the physical and physiological demands of football, followed by a critical review of the current evidence regarding monitoring training load, with special reference to the dose-response relationship. Furthermore, this literature review will provide an examination of the mechanisms that underpin fatigue and how fatigue might be monitored in an applied football environment.

2.2 Physical and Physiological Demands of Football

2.2.1 Match activity profiles

Football match play lasts 90 minutes, encompassing two periods of 45 minutes separated by a 15 minute interval. The ball is typically in play for 55-60 minutes (Bloomfield *et al.*, 2007). The remaining time is made up of throw-ins, set plays such as; free kicks, penalty kicks, goal kicks also, injury time and periods when the ball is out of play (Carling and Dupont, 2011). The analysis of activity profiling in football has evolved comprehensively since the initial studies (Reilly and Thomas, 1979, Bangsbo *et al.*, 1991). Early methods of football match activity profiling consisted of hand annotation and time-motion analysis systems, which were very time consuming compared to the more contemporary GPS and semi-automatic camera systems used today. These modern systems have presented a more sophisticated method of evaluating complex movements such as, maximum velocity sprinting, accelerations and decelerations.

Distances covered at the elite level are generally around 9-13 km for outfield players (Bradley *et al.*, 2009). Typically, centre midfield positions will cover the greatest total distance (TD) during games (∼12,000 m), suggesting that for these players aerobic capacity might be more important than for other positions. Central defenders are often reported as covering the least distance (∼10,000 m), with other positions (full backs, wide midfield and centre forwards) typically being similar to one another, covering ∼11,000 m (Bradley *et al.*, 2009). Furthermore, similar distances have been reported in youth academy football (Abbott *et al.*, 2018b). Recent research has highlighted that TD has remained consistent throughout a 7-year period in the English Premier League (Barnes *et al.*, 2014) and no differences are apparent between playing standards, with regards to distance covered (Bradley *et al.*, 2010). An appreciation of the TD covered during a game provides valuable information, however, without an understanding of the speeds at which that distance is covered and other demanding physical characteristics of match play, such as jumping, throwing, heading, dribbling and contesting with opponents, it is difficult to accurately assess the demands of competition.

During match play, a sprint occurs approximately every 90 seconds with each bout lasting an average of 3-5 seconds (Bangsbo *et al.*, 1991). Depending on the threshold used, sprinting (>25.2 $km.h^{-1}$) constitutes 150 – 300 m of the distance covered in a game, with substantial differences apparent between positions (Figure 2.1). Also, high speed running (>19.8 $km.h^{-1}$) displays some substantial differences between positions, with players covering on average 650 – 1100 m during match play (Di Salvo *et al.*, 2009).

Another important consideration when assessing the physical demands of football match play, is the acceleration and deceleration profile. Varley and Aughey (2013) found that acceleration efforts $\geq 2.78\ m\cdot s^{-2}$ occurred eight times more frequently than sprint efforts (>25 $km\cdot h^{-1}$). It was also found that 85% of these acceleration efforts did not result in speeds registered in the high speed threshold (>15 $km\cdot h^{-1}$). These findings highlight the importance of assessing the acceleration demands alongside speed demands. Following on from this study, Akenhead et al. (2013) assessed the temporal patterns of accelerations and decelerations during match play. They established time dependent reductions throughout a game and transient reductions following peak periods, suggesting that a players' capacity to perform optimally might be effected throughout match play.

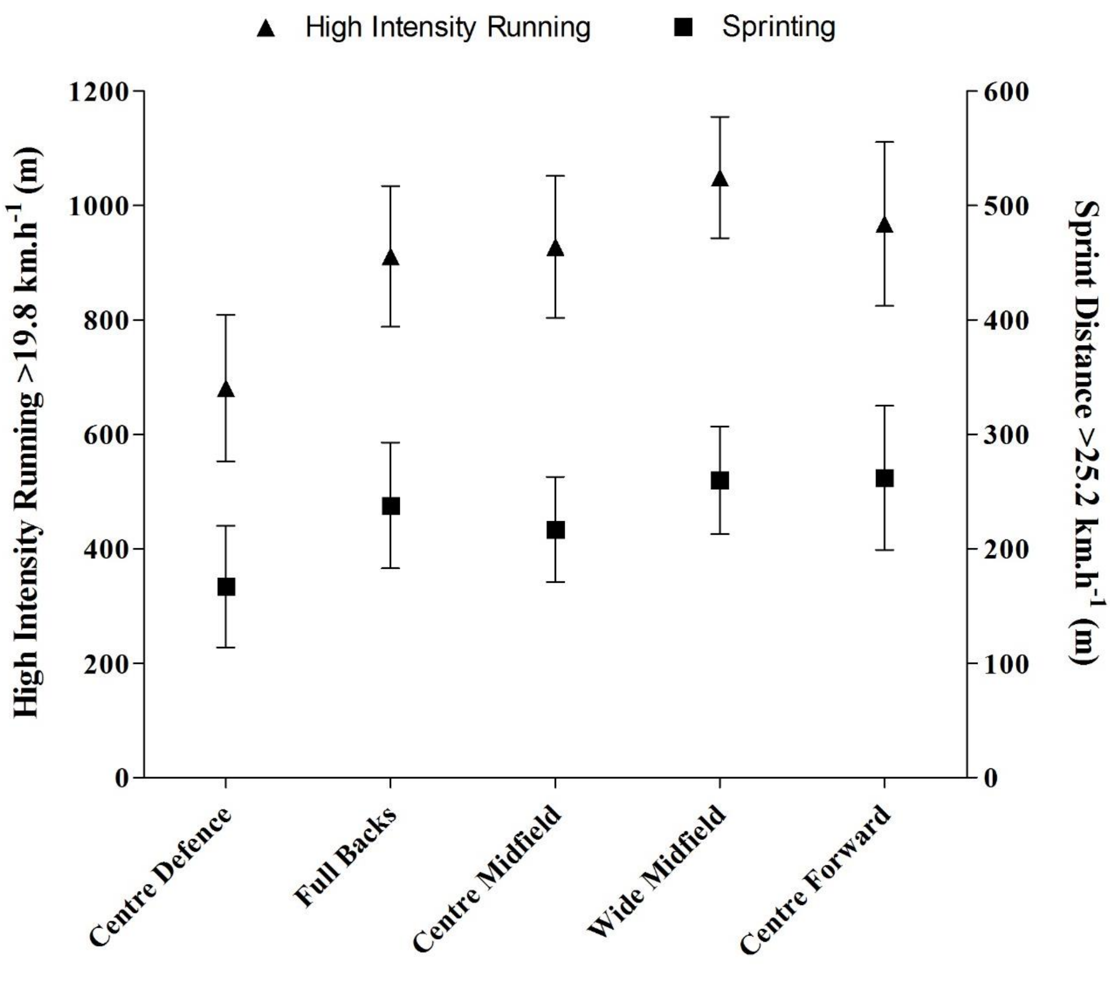

Figure 2.1. Distance covered while completing high speed running and sprinting by five outfield playing positions (Di Salvo et al., 2009). Error bars represent 1 SD.

2.2.2 Aerobic energy demands

Football is an intermittent sport during which the aerobic energy system is heavily taxed (Bangsbo *et al.*, 2006), with mean and peak heart rates (HR) of around 85 and 98% of maximal values, respectively (Ali and Farrally, 1991, Bangsbo, 1994). These HR measurements during a game appear to suggest that the average oxygen uptake ($\dot{V}O_2$) is around 70% of maximum $\dot{V}O_2$ ($\dot{V}O_{2max}$). There is a lack of literature regarding the precise $\dot{V}O_2$ profile during a football match, due to the difficulty of assessing $\dot{V}O_2$ in the field. However, portable gas analysers have been used to quantify the $\dot{V}O_2$ kinetics during various football activity patterns (Esposito et al., 2004). This research suggests a strong linear relationship between HR and $\dot{V}O_2$, concluding that the physiological demands of football activities can be estimated from HR measured in the field.

Some authors have suggested maximal aerobic capacity to be positively related to game performance and team success (Helgerud *et al.*, 2001, Hoff *et al.*, 2002). As previously mentioned average $\dot{V}O_2$ during match play is around 70% $\dot{V}O_{2max}$ (Stølen *et al.*, 2005), therefore, it is logical that an enhanced aerobic capacity would enable a player to reach and sustain a higher work rate and potentially exert a greater influence during a game. However the suitability and sensitivity of $\dot{V}O_{2max}$ as a determinant of football work rate has been questioned by some (Edwards *et al.*, 2003, Bangsbo *et al.*, 2006). A player's HR during a game is rarely below 65% of maximum, signifying that blood flow to the exercising musculature is continuously higher than at rest (Stølen *et al.*, 2005), indicating that oxygen utilisation by exercising muscles rather than oxygen delivery might be a more important factor (Christensen *et al.*, 2011).

The intermittent, repeat-sprint nature of football match play suggests a requirement for rapid $\dot{V}O_2$ on-kinetics in order to maximise the aerobic contribution to repeated high-intensity bouts, thus limiting reductions in performance caused by metabolic bi-products associated with anaerobic energy production (Mohr *et al.*, 2003, Magalhães *et al.*, 2010). Fast $\dot{V}O_2$ kinetics theoretically facilitate faster recovery and a reduced "oxygen debt", enabling repeat high-intensity efforts to be better maintained (Dupont *et al.*, 2005, Dupont *et al.*, 2010).

2.2.3 Anaerobic energy demands

Although aerobic metabolism is the major provider of energy during a football match, the most decisive actions are underpinned by anaerobic metabolism (Stølen *et al.*, 2005). Anaerobic energy production is high during football match play, indicated by the high number of brief intense actions (150 - 250) (Mohr *et al.*, 2003). Mean blood lactate concentrations of 2 – 10 $mmol.L^{-1}$ have been observed during football match play, with individual peak values reaching >12 $mmol.L^{-1}$ (Ekblom, 1986, Krustrup *et al.*, 2006). These findings indicate that the rate of muscle lactate production is high during match play. However, it is worth noting the differences observed between muscle and blood lactate. Krustrup et al. (2006) found weak correlations between muscle and blood lactate concentrations, this is likely due to differences in lactate turnover in the muscle compared to the blood, with the rate of lactate clearance being significantly higher in muscle than in the blood (Bangsbo *et al.*, 1993). Nonetheless, the high blood lactate and moderate muscle lactate concentrations during match-play suggested that the rate of glycolysis is high for short periods of time during a game. Furthermore, phosphocreatine (PCr) breakdown might be high, especially during shorter periods of high-intensity exercise, whilst re-synthesis of PCr levels might occur during periods of low-intensity exercise (Bangsbo *et al.*, 2006). Post-match muscle biopsies have shown PCr levels to be as low as 70% compared to pre-match concentrations (Krustrup *et al.*, 2006), with levels decreasing as low as 30% during elite football match-play (Bangsbo, 1994).

This section has discussed the physical and physiological demands of football match play, highlighting the need for excellent aerobic, anaerobic and sprint capabilities in order to meet the demands at the elite level. It could therefore be suggested that if players and/or teams are to succeed at the elite level methods for monitoring and improving these physiological and physical capabilities are of paramount importance to practitioners.

2.3 Football Training

2.3.1 Training structure

A typical training week or "micro-cycle" in elite level football will involve 4-6 training sessions and one competitive game, with the most demanding training sessions placed towards the beginning of the training week (Jeong *et al.*, 2011, Wrigley *et al.*, 2012). Early studies, quantifying training and match load via the session rating of perceived exertion (sRPE) reported that match load is approximately 18 to 25% of total weekly load (Impellizzeri *et al.*, 2004, Wrigley *et al.*, 2012). More recent studies have utilised the advancements in GPS technology to assess weekly external training demands over the course of a football season (Malone *et al.,* 2015a, Akenhead *et al.,* 2016). Malone *et al.* (2015a) assessed training micro-cycles on three occasions over a season in an elite football team. The authors found that training load was significantly reduced the day before match day (MD-1), with no differences observed across the remaining training days. They concluded that coaches might employ similar overall training load on the majority of training days, then attempt to unload on MD-1 in order to increase player readiness leading into the match. This could have important implications for training monotony, if training load is not correctly manipulated across the training week there could be inadequate recovery, accumulation of fatigue with subsequent effects on performance and injury risk (Foster, 1998). Akenhead *et al.* (2016) assessed daily training load over 18 in-season, 7-day micro-cycles, they found TD covered differed significantly across a 4-day training structure (Figure 2.2). Likewise, high speed distance (>21 $km.h^{-1}$) followed a similar pattern with a Tuesday (MD-4) displaying the highest load of the week. Comparable to the findings of Malone *et al.* (2015a), Akenhead *et al.* (2016) found players completed their lowest training load on MD-1.

Along with other studies that have assessed external training load in-season (Gaudino *et al.*, 2013, Owen *et al.*, 2016) it is apparent that the structure of the training week differs slightly in elite football from team to team, this will largely be depended on the philosophy of the manager and his staff (Weston, 2018). However, a similar pattern has arose, that players are "loaded" toward the start of the training week, both in terms of volume and intensity, and "de-loaded" leading into a game. Further research is need to understand how daily and weekly structure of training can impact on the relationship between training load, fitness, fatigue and performance.

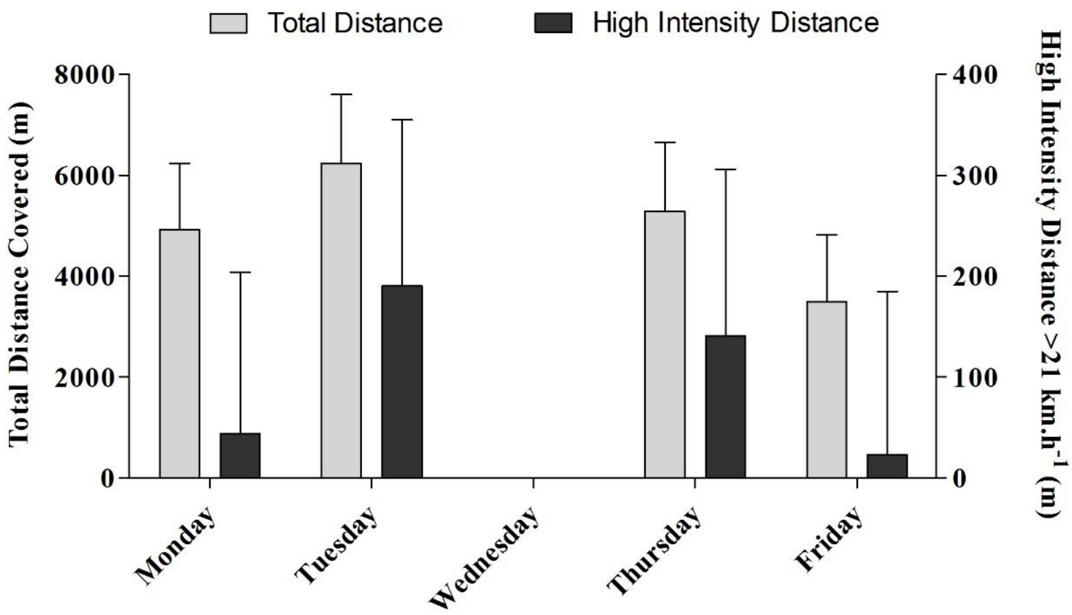

Figure 2.2. Weekly training structure for total distance and high speed distance as reported by Akenhead *et al.* (2016).

2.3.2 Training methodologies

Training programs and methodologies in elite football will largely be led by the clubs manager and his coaching/support staff. However, in modern football the methodologies used will most often be football specific and evidence based. One of the most popular methodologies is the use of small sided games (SSG). In SSGs players experience similar technical and tactical situations as they would encounter in competitive match play (Owen *et al.*, 2004). Due to this fact, game-based conditioning using SSG has become a popular method of developing specific aerobic and anaerobic fitness in football players (Impellizzeri *et al.*, 2006). There are a number of different constraints that can be manipulated during SSGs to alter the physiological, physical, technical, tactical and psychological demands of the training stimulus. Firstly, the number of players completing a SSG can elicit different outcomes. Studies have shown that SSG formats with fewer players elicit greater HR than larger numbered games (Owen *et al.*, 2004, Impellizzeri *et al.*, 2006, Rampinini *et al.*, 2007). However, as work-rate has been observed to remain consistent, irrespective of the number of players, it could be suggested that the increase in technical actions observed with fewer players also increases the physiological demands of SSGs (Jones and Drust, 2008). A substantial amount of research has investigated the impact of pitch size on the physiological and technical response to SSGs (Rampinini *et al.*, 2007, Kelly and Drust, 2009, Casamichana and Castellano, 2010), the findings however are conflicting. Kelly and Drust (2009) did not find any differences between the HR responses to three different pitch sizes. In contrast, Rampinini *et al.* (2007) and Casamichana and Castellano (2010) found significant differences in HR responses between SSGs played on pitches with different sizes, concluding there are higher HR values during SSGs played on a large pitch when compared to medium- and small sized pitches. Similar conflicting results have been found for technical actions, such as, passing, receiving, dribbling, interceptions and heading (Kelly and Drust, 2009). However, a higher number of shots and tackles has been found during SSGs on smaller pitches (Owen *et al.*, 2004, Kelly and Drust, 2009). These contrasting findings might be due to the differences in pitch size used. A review of SSGs by Aguiar *et al.* (2012) documented the large range of pitch sizes used within the literature; for example, a 6v6 SSG had a range of 240 - 2400 m^2. Perhaps an important consideration is the relative pitch space per player (m^2 per player), this can allow pitch sizes to be used that are comparable to 11v11 match play, resulting in greater distance covered, HSR and longer periods of ball possession, compared to smaller pitch sizes (Olthof *et al.*, 2018). A large number of constraints can also be used during SSGs to elicit different responses. It is beyond the scope of this review to discuss these in great detail, however these might include factors such as presence of goalkeepers and goals (Dellal *et al.*, 2008), coach encouragement (Rampinini *et al.*, 2007) and rule changes (Hill-Haas *et al.*, 2010). Although SSGs have been shown to prompt improvements in aerobic fitness (Impellizzeri *et al.*, 2006) the exact physiological and technical responses are often conflicting within the literature (Aguiar *et al.*, 2012). Furthermore, a criticism of SSGs is that they can potentially limit the amount of high speed and sprinting exposure players receive in training (Ade *et al.*, 2014) an important consideration when looking to improve performance and mange injury risk (Malone *et al.*, 2017b). While SSGs can be an important component of training, used to provide players with a sport specific stimulus, it could be suggested that in order to target specific physiological or physical qualities such as aerobic fitness or maximum sprint speed supplementary training should be completed.

2.3.3 Supplementary training

A range of supplementary training methods are utilised within football; aerobic and anaerobic conditioning, as well as speed, strength and power training. For the purpose of this review the focus will be on the use of running based conditioning drills to improve aerobic and anaerobic capabilities. Helgerud *et al.* (2001) conducted one of the first training studies that looked to evaluate the effects of an aerobic interval intervention on football performance. Their training intervention consisted of a 4 × 4 minutes running interval programme at 90–95% of maximum HR (HR_{max}), with three minutes active recovery between bouts. Following this training intervention improvements in $\dot{V}O_{2max}$ (11%), lactate threshold (16%), and running economy at lactate threshold (7%) were found. Similarly, the distance covered during a match increased by 20%, the number of sprints doubled and involvements with the ball during a match increased by 23%. Helgerud *et al.* (2007) further evidenced the efficacy of high intensity aerobic interval training when they compared the use of long slow distance running (continuous run at 70% HR_{max} for 45 min), lactate threshold running (continuous run at lactate threshold - 85% HR_{max} for 25 min), 15/15 interval running (47 repetitions of 15 s at 90-95% HR_{max} with 15 s of active rest at 70% HR_{max}) and the 4 x 4 minute protocol previously described. Results indicate the high intensity aerobic interval training of 15:15 and 4 x 4 minute performed at the same intensity both revealed significantly higher absolute $\dot{V}O_{2max}$ improvements of 5.5 and 7.3%, respectively, compared to the moderate and low intensity training groups. Concurrent improvements in stroke volume and cardiac output were also evident in the high intensity aerobic interval training groups indicating a strong dependence between these parameters. Although the evidence for the effectiveness of high intensity aerobic interval training based on percentage of HR_{max} is clear, the ability to programme and monitor interval training via HR telemetry is difficult in the field, given the need for constant live monitoring of each player. Furthermore, although the 4 x 4 protocol offers a significant reduction in volume compared to long slow distance running it still poses a substantial volume and time cost which might detract from football specific training.

An alternative method of programming high intensity interval training is to use the speed corresponding to $\dot{V}O_{2max}$ or maximal aerobic speed (MAS). Dupont *et al.* (2004) used a 15:15 protocol, completing 2 x 12-15 repetitions, running at 120% MAS over a 10 week period. Using this method players cover an individual distance determined according to their own MAS, over the same time period (15 s) while at the same relative intensity (120% MAS). Results indicated that a high intensity interval training program elicited an 8% improvement in MAS compared to normal football training, completed during a control period. More importantly this protocol was completed alongside habitual football specific training and shows that a high intensity interval training program based on % MAS can improve aerobic fitness, in-season, with minimal time cost (~15 minutes per session). Another popular supplementary training method is repeated sprint (RS) training. This is defined as “a series of short, maximal sprints (3–7 s in duration), separated by a short recovery period (<60 s)” (Buchheit and Laursen, 2013a). A comprehensive meta-analysis by Taylor *et al.* (2015) has highlighted that RS training can induce moderate (effect size; ES = 0.61) improvements in high-intensity intermittent running performance (Yo-Yo Intermittent Recovery Level 1; Yo-Yo IR1), RS ability, power and sprint speed, and therefore offers an effective strategy to improve a range of physical qualities, in a time efficient manner, in football players.

In conclusion, this section has reviewed the typical training structure, methodologies and supplementary training used in elite football. Although football specific methods such as SSGs offer an attractive option to coaches given their claim to enhance both the physical and technical qualities of players it has become apparent throughout this review that to improve specific physical qualities supplementary training might be advantageous. Thus, previous literature has clearly established the ability of supplementary running based protocols to improve aerobic fitness in football players. Methods such as MAS based interventions and RS training might offer the most effective and time efficient options for practitioners to use in order to improve a range of physical qualities, alongside habitual football training. Although the usefulness of these interventions is clear, how the cost they impose on the global training load of a football player and ultimately how they affect the training load, fitness and fatigue relationship is yet to be established.

2.4 Monitoring Training Load in Football

2.4.1 The training process

During the training process, players are regularly exposed to systematic and repetitive exercise stimuli with the goal of inducing adaptation and maximising performance. Other goals of the training process might include delaying the onset of fatigue and reducing the risk of injury. Player monitoring has become an integral component of the decision making process around the preparation of football players. Closely monitoring both training load and training response is essential to ensure a balance between exposure and recovery exists within the training plan.

The training process starts with the training plan in which a certain training dose (or training load) is prescribed by the coach. One of the first steps in the setup of a successful training monitoring system is to quantify the dose of training and matches. A conceptual model of the training process has been suggested by Impellizzeri et al. (2005).

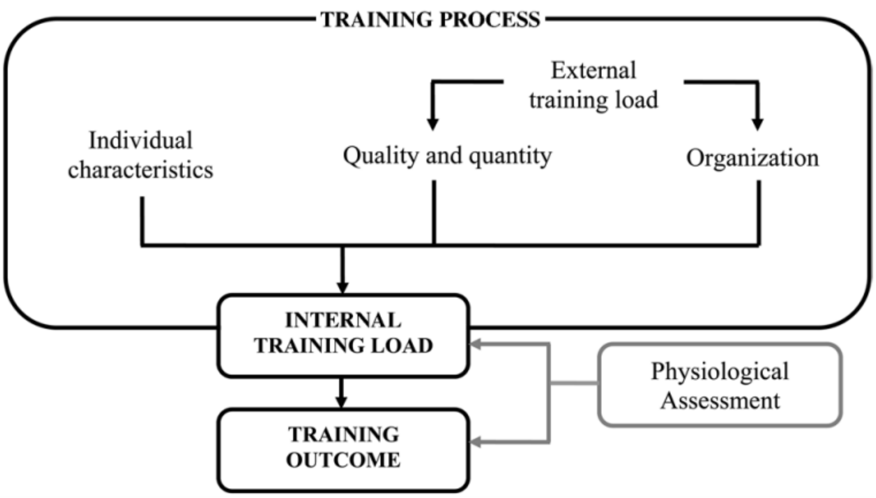

Figure 2.3. The training process as proposed by Impellizzeri *et al.* (2005).

The training dose can be monitored using both measures of internal and external training load. External training load is defined as the objective measure of the work that an athlete completes during training or match play and is measured independently of the internal training load (Halson, 2014). The internal training load is the physiological stress caused by training or competition. The magnitude of the stress imposed by training defines the subsequent adaptation (Halson, 2014). Internal training load ultimately determines training outcome, and is itself determined by a combination of external training load and individual characteristics (e.g. age, weight, fatigue state) (Figure 2.3).

2.4.2 The dose-response relationship

The efficacy and effectiveness of different training load methods is dependent on their ability to inform the training process and understanding the interactions between training load and the subsequent training outcome such as; fitness, fatigue and performance. Banister et al. (1975) proposed a simple model to explain the training response to a given training load and the resultant impact on performance. Banister et al. (1975) suggested that performance at any given time point is determined by two main components: a fitness response and a fatigue response (Figure 2.4).

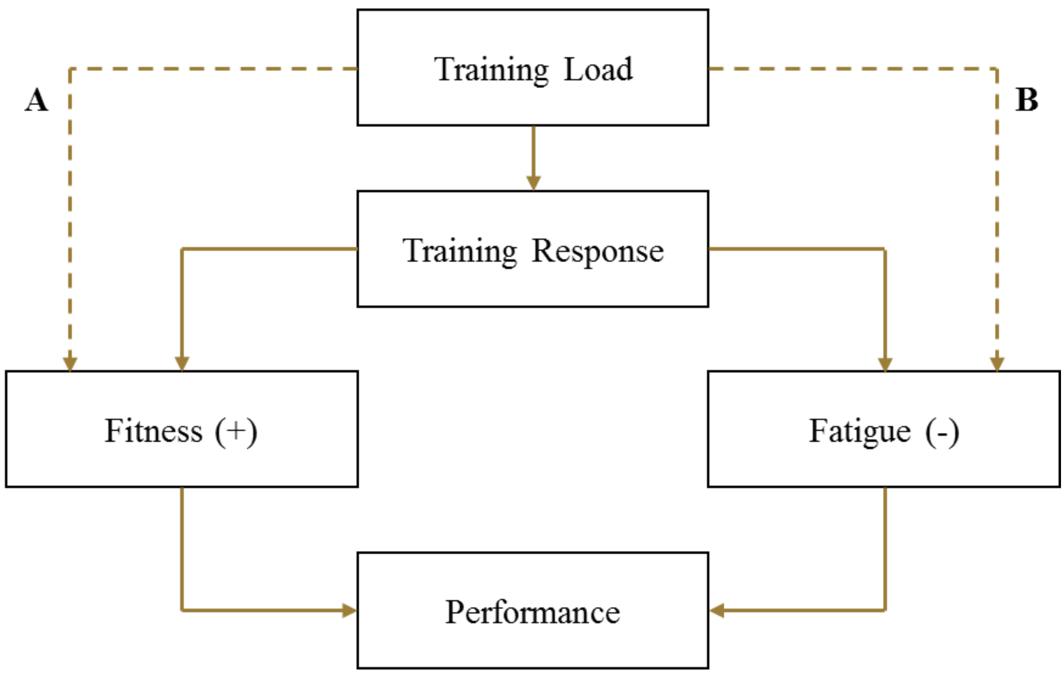

Figure 2.4. Conceptual model of the dose-response relationship (Banister et al. 1975).

The fitness response involves the physiological adaptation to training, which is the long term positive effect and will eventually result in an improvement in performance. The fatigue response is a shorter term negative effect caused by the training induced fatigue resulting in a decrease in performance (Banister et al., 1975). Therefore, Banister et al. (1975) suggest that, in its simplest form, performance at any time in a training program can be defined as the fitness gains in response to training minus the level of fatigue (Performance = Fitness – Fatigue). This relationship between training load, fitness, fatigue and performance is depicted in Figure 2.5. We can see that for a given training load there are simultaneous fitness (+) and fatigue (-) responses, while fatigue is greater than fitness the player is in a negative performance state. However, as fatigue dissipates at the quicker rate performance increases until the player is in a positive performance state.

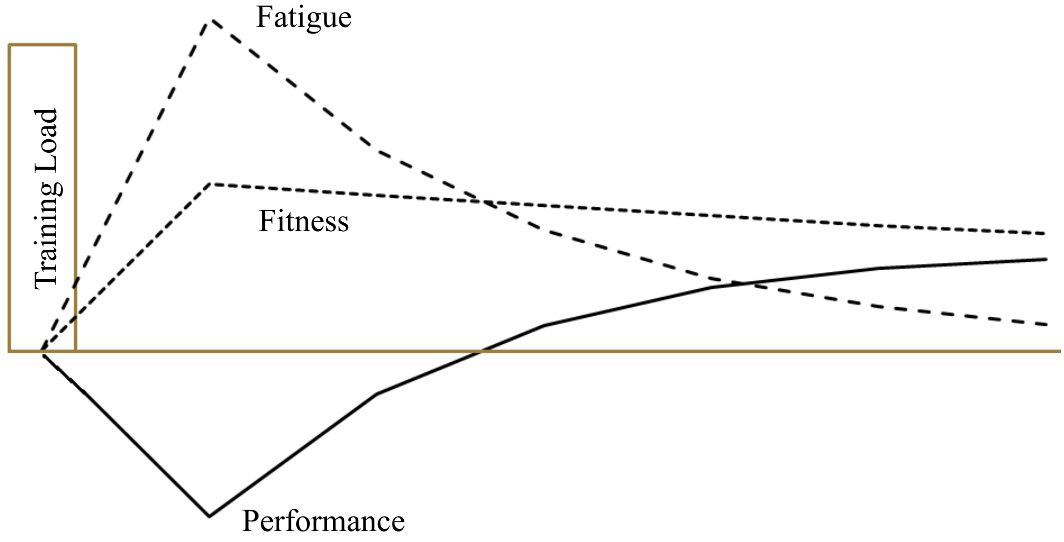

Figure 2.5. Representation of the training load, fitness, fatigue and performance model (Banister *et al.*, 1975).

2.4.3 External training load

External load refers to the total mechanical or locomotive work that is completed by a player, commonly expressed as a function of distance, speed or time. The use of GPS technology to monitor external training load in football is now common practice (Akenhead and Nassis, 2016, Weston, 2018). Furthermore, there are a plethora of studies within the literature that have used GPS to assess both match play and training. A search in PubMed for the term "GPS Soccer" will return 179 studies in November 2018. The validity and reliability of GPS to assess instantaneous velocity, accelerations and decelerations (Jennings *et al.*, 2010, Varley *et al.*, 2012, Akenhead *et al.*, 2014, Johnston *et al.*, 2014) has been established, indicating good validity and reliability. However, it should be noted that as constant velocity or acceleration increase the validity and reliability decrease.

The TD covered during training or match play is considered a general index of the players' workload (Aughey, 2011, Cummins *et al.*, 2013). External workload is often further categorised into speed zones in an attempt to understand the locomotor profile or intensity distribution of the players' loading. The way in which these speed zones are classified however varies greatly within the literature. For example HSR has been classified as low as 13 $km{\cdot}h^{-1}$ and as high as 24 $km{\cdot}h^{-1}$ (Jennings *et al.*, 2010). These dissimilarities in classification of speed thresholds, accompanied with differences in the technology available (Randers *et al.*, 2010), equipment manufacturers (Johnston *et al.*, 2014), sampling frequencies (Jennings *et al.*, 2010) software versions (Buchheit *et al.*, 2014) and data-processing techniques (Malone *et al.*, 2017a) make comparisons between studies and general recommendation about external training loads difficult. A recent survey of practitioners working in elite clubs across Europe has highlighted that arbitrary speed thresholds (>19.8 and >25.2 $km{\cdot}h^{-1}$) are most commonly used to quantify training load during training sessions and match play, along with TD and accelerometer variables. Scientific justification for the demarcation of speed zones is often lacking within the literature and in practice is frequently governed by the need to match thresholds to the semi-automated tracking systems used in football stadiums (i.e. ProZone/ Amisco Di Salvo *et al.* (2009)).

Another aspect of external training load which is important for practitioners to consider is the acceleration and deceleration demands of training and match play. The ability to accelerate has been associated with critical activities within football, such as being first to the ball, and creating/stopping goal scoring opportunities (Carling *et al.*, 2008). From a workload standpoint the research of Akenhead et al. (2013, 2015, 2016) has highlighted that not only is accelerating and decelerating an import component of match play workload (18% of TD covered >1 $m{\cdot}s^{-2}$), but also there is a higher physiological cost (increase blood lactate values and RPE) associated with accelerating compared to steady running. Therefore it is suggested that acceleration and deceleration are an important aspect when evaluating external load in football, however, the dose-response relationship between acceleration and declaration and specific training outcomes has yet to be established.

An additional method utilised by practitioners to quantify external load is tri-axial accelerometer data. In team sport research, the most commonly used tri-axial accelerometer data, is referred to as PlayerLoad™ (PL), defined by the manufacturers, to provide an overall external load for an individual as it encompasses running and non-running events in all planes of motion (vertical, mediolateral and anterior-posterior), such as running, jumping, tackles and changes of direction (Boyd *et al.*, 2011). There are strong correlations between PL and TD covered during football training activities (r^2-0.83; Scott *et al.* (2013a)). Furthermore, PL and its individual component planes have shown within-match patterns during games, showing that locomotor efficiency (PL per metre covered) increases towards the end of each half, which might be representative of fatigue (Barrett *et al.*, 2016). However, it is important to acknowledge the current limitations of tri-axial accelerometer data. Recent research has suggested that the accuracy of estimated ground reaction forces, as a measure of whole body biomechanical loading is poor (Verheul *et al.*, 2019). Caution should therefore be applied when interpreting accelerometer data, particularly from one segment (MEMS device between the scapulae), as it is unlikely to represent external whole body biomechanical loads. No studies to date have utilised tri-axial accelerometer data as an external load measure when assessing the dose-response relationship with specific training outcomes.

There have only been two studies which have used external load to investigate the dose-response relationship between training load and measures of fatigue in football (Thorpe *et al.*, 2015, Scott and Lovell, 2017). Thorpe *et al.* (2015) findings show that subjective ratings of player wellness, specifically perceived fatigue display *large* (r =-0.51) associations with fluctuations in daily HSR (>14 $km \cdot h^{-1}$). Other markers assessed such as countermovement jump (CMJ) height and HR indices showed *trivial* to *small* (r = 0.13 – 0.23) associations with external load. The authors concluded that a limitation was the arbitrary nature of their external load measure, suggesting, the use of individualised speed thresholds that take into account each individuals physiological characteristics might represent a better way of quantifying training load. Building on this work, Scott and Lovell (2017) assessed the relationship between external training load and subjective wellness, using both arbitrary and individualised HSR measures. They found small to moderate (r = -0.19 to -0.31) relationships between training load and subjective measures of fatigue and muscle soreness. Furthermore, no clear differences were observed between arbitrary and individualised speed thresholds. It could be suggested however, that methodological issues, resulted in the questionable relationships found in the two aforementioned studies. Both studies assessed training load and fatigue daily throughout a short training period (17-21 days), this does not allow for the training dose to be standardised or for the potential accumulation of fatigue. Similar studies under more controlled training conditions are therefore warranted.

2.4.4 Internal training load

Internal training load measures are typically based on either HR or a subjective RPE (Banister and Calvert, 1980, Foster *et al.*, 1996). Banister and Calvert (1980) developed a training load measure based on HR to define the dose of exercise in training impulse (TRIMP) units. Banister's TRIMP was defined as:

$$\text{TRIMP} = \text{duration training (min)} \times \Delta\text{HR} \times y$$

$$\Delta\text{HR} = (\text{HR}_{ex} - \text{RHR}) / (\text{HR}_{max} - \text{RHR})$$

Where HR_{ex} is exercise HR, and RHR is resting HR. The weighting factor (y) is based on typical blood lactate profile in trained males and females (Banister and Calvert, 1980).

Banister's TRIMP uses mean HR during exercise to quantify internal training load. Following the original TRIMP method proposed by Banister and Calvert (1980), several modifications to the method have been proposed. Edwards (1993) proposed a different HR-based TRIMP method using five arbitrary HR zones with each zone weighted from one to five where the duration spent in each zone is multiplied by the weighting factor to provide a total TRIMP score. Lucia *et al.* (2003) proposed a three zone-based TRIMP method. The three zones are based around physiological thresholds: zone one is below the ventilatory threshold, zone two is between the ventilatory threshold and the respiratory compensation point and zone three above the respiratory compensation point. Weighting factors are defined as an arbitrary one, two and three for each zone respectively. More recently, Manzi *et al.* (2009b) proposed another modified TRIMP method called iTRIMP. For iTRIMP, the weighting factors are calculated using each players individual HR – blood lactate response taken from an incremental exercise test.

RPE is another popular method for quantifying internal load (Impellizzeri *et al.*, 2004). The original RPE scale as developed by Borg *et al.* (1987) used a 15-point scale of 6 to 20, anchored with words contextualising the scale against subjective perceptions of effort. The original scale was developed to match typical absolute HR during exercise (60 to 200 $b.m^{-1}$). Several modifications of the scale have been proposed, the most commonly utilised being the 11 point scale (0 to 10) (Borg and Kaijser, 2006). Foster *et al.* (1996) first proposed using sRPE which is the product of RPE and the duration of exercise. However, both the validity (Chen *et al.*, 2002) and reliability (Scott *et al.*, 2013b) of RPE has been questioned within the literature. For example, the sRPE recorded for the same external workload has been shown to vary depending on the distribution of exercise intensity across the exercise session (Scott *et al.*, 2013b). However, as RPE is a measure of perceived load it is possible that psychosocial factors can influence ratings, it could therefore be suggested that RPE is a good measure of universal training load.

Two studies have investigated the dose-response relationship between internal training load and measures of fitness in football players. Akubat *et al.* (2012) assessed a range of internal training load measures over a 6-week training period, assessing aerobic fitness pre and post. Results suggest that changes in the speed at lactate threshold are correlated to mean weekly iTRIMP (r = 0.67). Banisters TRIMP and sRPE did show moderate correlations with speed at onset of blood lactate accumulation (r = 0.40 – 0.43), however, these relationships were non-significant, potentially due to the small sample size (n = 9). Similarly, Manzi *et al.* (2013) monitored iTRIMP during an 8-week pre-season period in elite football players and assessed measures of aerobic fitness pre and post. They found that accumulated iTRIMP was significantly correlated to improvements in $\dot{V}O_{2max}$ (r = 0.77), ventilatory threshold (r = 0.78) and Yo-Yo IR1 performance (r = 0.69). These two studies suggest that it is an individual's internal response to training which dictates the changes in aerobic fitness. However, no studies to date have assessed this relationship using external load measures.

2.4.4 Individualised external training load

It is well established that the internal response to training load is what drives the training outcome (Impellizzeri *et al.*, 2005). This is therefore a limiting factor when assessing the external workload of players through systems such as GPS. An alternative method might be to use individualised speed thresholds based on the physiological characteristics of the individual player. This will provide an "internalised" measure of external load, which might improve the relationships with specific training outcomes (Akubat, 2014).

Abt and Lovell (2009) first proposed that high speed thresholds, should be individualised based on the second ventilatory threshold in a similar manner to the methods proposed by Lucia et al. (2003). Abt and Lovell (2009) found the median velocity at the second ventilatory threshold to be 15 km.h^{-1}. This resulted in a three-fold increase in the quantification of HSR distance covered compared to the arbitrary distance covered above 19.8 km.h^{-1}. Although this is an obvious finding as the threshold for high speed has been substantially reduced, this highlights that true high speed activity might be substantially underestimated when using higher arbitrary thresholds. Although these findings show the need to individualise training loads based on physiological characteristics, the methods used by Abt and Lovell (2009) require extensive laboratory testing which might not be feasible in an applied football environment. Other methods have been employed to assess players training load with reference to individual fitness characteristics gained via field based assessments. Percentage of maximum sprint speed (MSS) has been used previously (Harley *et al.*, 2010), however, it has been highlighted that using one single fitness characteristic might not reflect the complete locomotor profile of a player (Weston, 2013, Hunter *et al.*, 2015). Alternatively, Mendez-Villanueva et al. (2013) used a technique which encapsulated field based testing data to estimate a players' MAS and sprint capabilities (MSS). This technique allows for an estimation of a players' anaerobic speed reserve (ASR) and has been used to establish a players' transition (>30% ASR) into anaerobic workload (Bundle *et al.*, 2003, Mendez-Villanueva *et al.*, 2013). More recently, Hunter et al. (2015) compared a number of different methods for individualising speed thresholds (Table 2.1), including both laboratory and field based measures. They discussed that an approach using laboratory derived thresholds of respiratory compensatory threshold and speed at $\dot{V}O_{2max}$ (s$\dot{V}O_{2max}$) would be the gold standard method for individualising speed thresholds. However, a method using field based measures of MAS, MSS and ASR poses an ecologically valid, economical and practical technique for individualising thresholds.

Table 2.1. Description of methods used to categorise speed thresholds (Hunter *et al.*, 2015).

	ARB	**IND**	**MAS**	**MSS**	**LOCO**
Low-Speed Running	< 14.99	< RCT	< 79% MAS	< 49% MSS	< 79% MAS
High-Speed Running	15.00 - 17.99	RCT - $s\dot{V}O_{2max}$	80-99% MAS	50-59% MSS	80% -99% MAS
Very High-Speed Running	18.00 - 24.99	$s\dot{V}O_{2max}$ - 29% ASR	100-139% MAS	60-79% MSS	100% MAS - 29% ASR
Sprinting	25.00 – 35.00	30% ASR – MSS	140% MAS - 35 $km.h^{-1}$	80% - 100% MSS	30% ASR - MSS

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

Studies that have used MAS to individualise speed thresholds from field based assessments have tended to use a modified version of the Montreal Track Test (Leger and Boucher, 1980) and the VAM-EVAL (Mendez-Villanueva *et al.*, 2013, Hunter *et al.*, 2015, Abbott *et al.*, 2018a). Another method that might provide a simple and effective estimate of MAS is time trial performance. Multiple studies have shown that MAS can be estimated from the average speed during a time trial for any distance between 1200 and 2200 metres (Lorenzen *et al.*, 2009, Bellenger *et al.*, 2015). However, the reliability and/or usefulness of such a test to individualise speed thresholds has yet to be established.

One study to date has utilised individualised speed thresholds to assess the dose-response relationship between training load and measures of fatigue (Scott and Lovell, 2017). As previously discussed, they found small to moderate (r = -0.19 to -0.31) relationships between training load and subjective measures of fatigue and muscle soreness. However, no clear differences were observed between arbitrary and individualised speed thresholds, calling into question the utility of individualised training load for assessing the does-response relationship with fatigue. These findings might be a result of the acute nature of this study that correlated daily training load with subjective fatigue. It is likely that acute daily differences between arbitrary and individualised measures; for example from one training session, are small. However, when these small differences are accumulated over time distinctions might be more apparent. No studies to date have assessed the chronic dose-response relationship between individualised training load and changes in fitness, furthermore, this is a topic that has been highlighted within the literature as needing further investigation (Drust, 2018).

2.5 Fatigue in Football

Previous sections within this literature review have introduced the importance of the dose-response relationship and provided an overview of the current literature on monitoring training load in football. The following sections will look to discuss the training response, with special reference to fatigue. An overview of the mechanisms behind fatigue in football will be undertaken and a holistic view of the methods used to monitor fatigue will be discussed.

The broad use of the term fatigue within the literature presents a challenge as this can encompass several different phenomena that are the consequence of different physiological and perceptual processes (Enoka and Duchateau, 2008). In the field of sports science the consequences of fatigue have been defined as "a failure to maintain the required or expected force" (Edwards, 1981) and "an exercise-induced reduction in the ability of muscle to produce power or force" (Bigland-Ritchie and Woods, 1984). However, these definitions focus on the physiological consequences of fatigue, mainly reductions in muscular force. Another important aspect of fatigue, that needs consideration, is the perceptual component. Other researchers have defined fatigue as “the conscious perception of changes in subconscious homeostatic control systems” (St Clair Gibson *et al.*, 2003), this suggests that fatigue is a sensation experienced by the exerciser that is critical to the regulation of exercise intensity. It has therefore been recommended that a consideration of both the physiological and perceptual consequences are necessary to understand the phenomena of fatigue during exercise (Barry and Enoka, 2007). For the purpose of this thesis the operational definition of fatigue will be “an inability to maintain optimal performance due to physiological and perceptual changes”.

2.5.1 Metabolic fatigue

As discussed in previous sections the activity profiles, and in particular high-intensity running have been seen to fall significantly during the final periods of a football match (Reilly and Thomas, 1979, Mohr *et al.*, 2003, Krustrup *et al.*, 2006). The exact underlying mechanism for the apparent reduction in physical performance towards the final stages of match play remain unclear, largely due to the numerous technical and tactical influences. The source of energy in high-intensity exercise depend predominantly on muscle glycogen rather than extracellular glucose (Jacobs *et al.*, 1982). Muscle glycogen stores have been shown to be almost fully depleted after a football match (Saltin, 1973). More recently, less severe reductions in muscle glycogen have been found post-match, although further analysis revealed over half of the individual type I and II fibres showed depleted or partially depleted glycogen capacity, particularly in fast twitch fibres (Krustrup *et al.*, 2006). Interestingly, the depletion of glycogen in fast twitch fibres to a critically low level where maximal glycolytic rate cannot be maintained (Bangsbo *et al.*, 1992) was shown to determine the point of fatigue during match play (Krustrup *et al.*, 2006). Therefore, the substantial reduction of muscle glycogen observed in individual fibres could hamper the ability to maximal exert force and consequently decline single and repeated sprint performance.

In addition to fatigue towards the end of a match, time motion analysis has indicated that transient fatigue might also occur during match play (Mohr *et al.*, 2003, Akenhead *et al.*, 2013, Barrett *et al.*, 2016), with a reduced ability to undertake high-intensity running, sprinting and acceleration during the five minute period following the most intense period of the game. Furthermore, it was shown that following an intense period of match play, sprint performance was significantly reduced when compared to sprint performance at the end of the first half (Krustrup *et al.*, 2006). An exercise-induced elevation of lactate and the associated increase in hydrogen ions (H^+) within the muscle are thought to contribute to the temporary decrement in performance during these intense periods. In addition to acidosis, anaerobic metabolism in skeletal muscle also involves hydrolysis of creatine phosphate to creatine and inorganic phosphate (Pi). It has been suggested that Pi might be a major cause of fatigue during high intensity exercise (Westerblad *et al.*, 2002). Increased Pi has been shown to substantially impair myofibrillar performance, decreases sarcoplasmic reticulum calcium release and therefore contributes to the decreased activation (Allen and Trajanovska, 2012).

The rapid depletion of adenosine triphosphate (ATP)/ PCr and the relative short time to replenish PCr stores is suggested to influence the ability to perform subsequent bouts of high intensity activity, and consequently contribute to a decline in performance during match play (Bangsbo, 1994). However, biopsy studies during football match play indicate PCr is only reduced by 25% following a high intensity period (Krustrup *et al.*, 2006). It must be noted however, that the values in the aforementioned study might have been underestimated as a result of the rapid recovery of PCr stores and the delay in obtaining the muscle biopsy. Indeed, PCr might deplete individual fibres almost completely following intense activities (Soderlund and Hultman, 1991).

Another proposed factor in the onset of temporary fatigue in football is an accumulation of potassium ions (K^+) in the muscle interstitial metabolism and the resulting electrical disturbances in the muscle cell (Bangsbo *et al.*, 1996). This was in agreement with another study, which reported a significant increase in interstitial K^+ concentrations during exhaustive exercise with a simultaneous decline in muscle pH (Nordsborg *et al.*, 2003). Training studies have demonstrated that intense intermittent training reduces accumulation of K^+ in muscle interstitial during exercise, through a larger re-uptake of K^+ and greater activity of the muscle sodium-potassium pumps. Subsequently, the lower accumulation of K^+ in muscle interstitial delayed fatigue during intense exercise, supporting the notion that K^+ accumulation is involved in the development of fatigue (Nielsen *et al.*, 2004). With reference to football, studies have shown that plasma K^+ levels can be elevated to levels around that observed following exhaustive incremental intermittent exercise (Krustrup *et al.*, 2003). The intermittent nature of football means that a myriad of factors and mechanisms could lead to fatigue in players. Metabolic factors such as reductions in ATP, PCr, glycogen and muscle pH, coupled with accumulation in muscle lactate, H^+, Pi and K^+ might contribute to the diminishing physical performance.

2.5.2 Neuromuscular fatigue

Neuromuscular fatigue can relate to any alteration in the physiological processes governing the central nervous system or muscle function, but is typically quantified by examining voluntary and artificially-evoked forces during an isometric muscle action (Thomas *et al.*, 2018). Peripheral mechanisms of fatigue operate at, or distal to, the neuromuscular junction with central fatigue being defined as a progressive reduction in voluntary activation of a muscle (Carroll *et al.*, 2016). There is a tendency within the literature to use the term neuromuscular fatigue, when assessing physical performance measures such as jump or sprint tests, however, although these measures might relate to muscle function they are not specifically assessing neuromuscular fatigue. For the purpose of this review the term neuromuscular fatigue will signify the assessment of muscle function through peripheral or central pathways.

Peripheral fatigue is a consequence of impairments in contractile function and central fatigue, the capacity of the central nervous system to activate muscle (Gandevia, 2001). Peripheral contributors to muscle fatigue can be assessed by measuring involuntary responses to electrical stimulation at rest. Additionally, central contributors can be examined through responses to electrical and magnetic stimulation during voluntary contractions (Thomas *et al.*, 2018). Three studies to date have investigated the central and peripheral mechanisms associated with match related fatigue (Rampinini *et al.*, 2011, Thomas *et al.*, 2017, Brownstein *et al.*, 2017). Firstly, Rampinini *et al.* (2011) observed significant moderate-to-large correlations between voluntary activation (central marker) and TD covered in elite players. No correlations were found between physical match performance characteristics and peripheral markers of fatigue. Rampinini *et al.* (2011) concluded that central fatigue seems to be the main cause of the decline in maximum voluntary contraction and sprinting ability, whereas peripheral fatigue seems to be more related to increased muscle soreness and therefore seems very likely linked to muscle damage and inflammation. Similarly, Thomas *et al.* (2017) found a simulated football match resulted in substantial fatigue that persisted for up to 72 h post exercise. Central fatigue, determined via voluntary activation, was substantially reduced immediately post exercise and, although markedly recovered by 24 h, remained significantly depressed for 48 h post exercise. Peripheral fatigue was substantial immediately post exercise, remained similarly depressed at 24 h, and was still below baseline at 72 h. They suggest, this marked and prolonged nature of peripheral fatigue indicated that changes in skeletal muscle function primarily explained the resolution of neuromuscular fatigue in the days after football match play. Further, these peripheral changes are likely related to muscle damage, as evidenced by the large increase in creatine kinase (CK) in the days post exercise, and the subsequent inflammatory response rather than processes within the central nervous system.

2.5.3. Exercise induced muscle damage

High-intensity actions such as sprinting, high-speed running, acceleration, deceleration, jumping, tackling, and are repeatedly performed over the course of a football match (Di Salvo *et al.*, 2009, Akenhead *et al.*, 2013). Indeed, sprinting; changes in direction; acceleration and deceleration actions involve eccentric contractions which have previously been associated with the potential to induce muscle damage (Byrne *et al.*, 2004). Muscle damage is characterised by a temporary reduction in muscle function, an increase in intracellular proteins in the blood, an increase in perceptual muscle soreness and evidence of swelling (Howatson and Van Someren, 2008). Initially, muscle damage results from a mechanical disruption of the muscle fibre, including membrane damage, myofibrillar disruptions characterised by myofilament disorganisation and a loss of Z-disk integrity (Raastad *et al.*, 2010). Secondary damage is linked to the subsequent inflammatory response and infiltration of neutrophils that further compromise the mechanically damaged area (Butterfield *et al.*, 2006). Elevated levels of muscle damage markers have been reported at the end of a football match (Ispirlidis *et al.*, 2008, Silva *et al.*, 2013). Exercise induced muscle damage derived from high-intensity activity involving an eccentric component could therefore, contribute to a reduction in physical performance seen during match play.

2.5.4 Time course of recovery in football

In order for practitioners to have an impact on training load management and recovery strategies in the days post match play, understanding the time course of recovery is of vital importance. Studies that have assessed the time course of recovery tend to focus on physical performance measures, neuromuscular function, subjective measures and biochemical markers, with the majority of studies assessing a range of measures concurrently (Ascensão *et al.*, 2008, Ispirlidis *et al.*, 2008, Fatouros *et al.*, 2010, Rampinini *et al.*, 2011, Brownstein *et al.*, 2017, Thomas *et al.*, 2017).

Sprint performance is compromised immediately after exercise by -3% to -9% (Magalhães *et al.*, 2010, Rampinini *et al.*, 2011). Thereafter, the recovery of sprint performance differs largely between studies with complete recovery occurring between 5 (Andersson *et al.*, 2008) and 96 h (Ispirlidis *et al.*, 2008). When tested immediately after exercise, CMJ jump performance ranged from no decrement (Thorlund *et al.*, 2009) to -12% (Magalhães *et al.*, 2010, Thomas *et al.*, 2017). Jump performance completely recovered from 48 h (Ispirlidis *et al.*, 2008, Fatouros *et al.*, 2010) to more than 72 h after exercise (Andersson *et al.*, 2008, Magalhães *et al.*, 2010).

Football match play has provoked neuromuscular fatigue that is both central and peripheral in origin (Rampinini *et al.*, 2011, Brownstein *et al.*, 2017, Thomas *et al.*, 2017). Brownstein *et al.* (2017) assessed voluntary activation, measured through motor point stimulation following a competitive match. They found significant reductions post-match (7.1%) and at 24 h (4.7%), before recovering by 48 h. The magnitude of impairments and time-course of recovery of central fatigue was similar to that reported previously

(Rampinini *et al.*, 2011, Thomas *et al.*, 2017). Thomas *et al.* (2017) found peripheral fatigue, evidenced by reductions in quadriceps potentiated twitch force, was substantial post match (-14%), persisted at 24 h post match (-13%) and remained under baseline at 48 h (-8%) and 72 h (-5%). These results suggest the neuromuscular fatigue experienced in the days post match play can be explained to a greater extent by processes occurring within the muscle, that are likely related to muscle damage and the subsequent inflammatory response rather than processes within the central nervous system (Thomas *et al.*, 2017).

The assessment of subjective wellness has been used to measure sensations of fatigue, muscle soreness, sleep quality and stress in football players post match play (Ispirlidis *et al.*, 2008, Fatouros *et al.*, 2010, Brownstein *et al.*, 2017, Thomas *et al.*, 2017). This research highlighted that perceptual fatigue and muscle soreness is evident post match and can persist for more than 72 h, which is longer than the time course observed for physical performance and neuromuscular fatigue (Brownstein *et al.*, 2017). A lack of association between subjective and objective measures of fatigue has previously been reported (Saw *et al.*, 2015b), and provides support for the inclusion of both when assessing recovery following match play. This might provide a more comprehensive understanding of a players physiological and perceptual levels of fatigue.

Biochemical markers found in blood plasma and saliva have been used to evaluate the physiological mechanisms associated with fatigue post match play. Markers of muscle damage, inflammation, immune status, oxidative stress and hormone activity have been assessed (Bangsbo *et al.*, 2006, Ispirlidis *et al.*, 2008, Morgans *et al.*, 2014, Brownstein *et al.*, 2017, Thomas *et al.*, 2017). Muscle proteins, such as CK, leak into the plasma from skeletal muscle fibres when they are damaged. Increases in CK have been seen immediately post-match (>200%) and have peaked between 24-48 h (>700%) and return to baseline values from 72-120 h (Magalhães *et al.*, 2010, Ispirlidis *et al.*, 2008). Large discrepancies within the literature are apparent, which might be due to questionable validity and reliability (Nédélec *et al.*, 2012). However, CK is widely used as the magnitude of increase is so great relative to other proteins. Moreover, CK remains elevated for several days compared to other proteins so might be useful for assessing muscle damage and the inflammatory response, which could be the cause of delayed onset of muscle soreness.

This section has provided an overview of the potential mechanisms of fatigue, such as metabolic fatigue, neuromuscular fatigue and exercise induced muscle damage. Following this, the time course of recovery was discussed, highlighting that fatigue might be apparent for up to 72 h post match play, however, there are some large differences between studies. Several mechanisms are possible to explain these differences between studies in the magnitude of fatigue and the subsequent recovery time course. Firstly, there is high variability and poor reliability of physical outputs during match play, such as high-intensity running (Gregson *et al.*, 2010). Secondly, contextual factors, such as, match outcome, quality of the opposition and match location might influence physical outputs (Lago-Peñas *et al.*, 2011, Barrett *et al.*, 2018). Collectively, all these factors contribute to a level of fatigue that might vary greatly from one match to another. One possible solution to this problem might be to assess fatigue in a training environment. This can allow for the load placed upon players to be more carefully standardised, whilst still providing a football specific stimulus from which to assess fatigue.

2.6 Monitoring Fatigue in Football

The mechanisms of fatigue and time course of recovery were outlined in the previous section, however, for practitioners the ability to monitor the fatigue response of their players on a daily or weekly basis is of upmost importance. In order to be used as a valid indicator of fatigue in an applied environment, potential tools should be simple, quick, non-invasive and easy to administer. Furthermore, potential measures should be sensitive to fluctuations in training load and their response to acute load should be distinguishable from chronic changes in adaptation (Meeusen *et al.*, 2013). Due to logistics, time and financial cost, subjecting athletes to frequent rigorous laboratory testing that is widely regarded as the gold standard, does not represent a feasible option. As such, practitioners and researchers seek assessments that are associated with physiological measures and that can be utilised in the field. The remainder of this section will discuss the various potential methods that have been proposed for this purpose.

2.6.1 Subjective measures

Subjective measures, often collected through psychometric questionnaires, are widely used in team sports (Taylor *et al.*, 2012a, Akenhead and Nassis, 2016). A recent review emphasised that subjective measures might report greater sensitivity to acute and chronic training load, fitness and fatigue compared to objective measures (Saw *et al.*, 2015b). However, there has yet to be a consensus on the most appropriate questionnaire to be used. Profile of Mood States (McNair *et al.*, 1981), Recovery-Stress Questionnaire (Kellmann and Kallus, 2001) and Daily Analyses of Life Demands (Rushall, 1990) are just some of the assessment tools which have been used within the literature. However, their length, narrow focus or lack of specificity to the sporting context has led many sports programs to develop their own questionnaires (Saw *et al.*, 2015a). Subsequently, practitioners and researchers have incorporated customised, shortened questionnaires into their monitoring practices and research (Hooper and Mackinnon, 1995, McLean *et al.*, 2010). However, the reliability and sensitivity of these shortened wellness questionnaires is largely unknown. Research in the Australian-Rules Football League (AFL) has shown custom psychometric scales to be sensitive to daily, weekly and seasonal changes in training load (Buchheit *et al.*, 2013, Gastin *et al.*, 2013). Furthermore, daily subjective wellness (fatigue, muscle soreness, sleep quality, stress and mood) was significantly correlated with daily variations in training load in a pre-season camp in AFL players (Buchheit *et al.*, 2013). More recently, research has established the dose-response relationship between training load and subjective measures in football (Thorpe *et al.*, 2015, Scott and Lovell, 2017). Results indicate that subjective fatigue and muscle soreness are sensitive to acute changes in training load, and often outperform other objective measures of fatigue. Within the literature, there is still limited evidence around the reliability of subjective measures. Furthermore, the lack of guidelines regarding how to interpret and act upon changes in subjective measures, and what changes are practically meaningful, poses a future challenge for researchers and practitioners.

2.6.2 Physical performance measures

Various maximal jumping and sprinting based protocols have been employed as surrogate measures of neuromuscular function by practitioners and researchers attempting to monitor fatigue. The previous section of this review highlighted that CMJ has been used extensively to assess post match play fatigue and recovery, with decrements in performance evident for up to 72 h (Andersson *et al.*, 2008, Magalhães *et al.*, 2010). However, less attention has been given to the utility of jump performance measures as a regular monitoring tool, and their sensitivity to changes in training load. From the studies that have utilised jump performance as a monitoring tool, the results appear in conflict with those reported in match play fatigue studies. CMJ performance was not sensitive as a measure of fatigue status in elite youth players when analysed alongside daily fluctuations in training load (Malone *et al.*, 2015b). Furthermore, a study into adolescent football players revealed no change in CMJ height or correlation to training load during a three week training period (Buchheit *et al.*, 2010a). Thorpe *et al.* (2015) found a small positive correlation (r = 0.23) between HSR and changes in CMJ height, proposing that HSR might have had a priming/ potentiating effect on the following days CMJ performance.

It has been suggested that alternative parameters to height, which can be derived from a CMJ might provide greater sensitivity to fatigue (Gathercole *et al.*, 2015). Of the 22 variables analysed from a CMJ, 18 showed substantial changes post exercise, they concluded that as well as jump height, the movement strategy should also be assessed (e.g. eccentric and concentric time, flight time: contraction time ratio [FT: CT]). Furthermore, studies by Cormack et al. (2008a, 2008b) identified that CMJ height might lack the necessary sensitivity to detect changes in fatigue post match play and over the course of an AFL season. They suggested that as CMJ height was a performance outcome, small alterations in technique might be able to maintain height and mask the effects of fatigue. Cormack et al. (2008a, 2008b) proposed that force-time variables, such as the FT: CT ratio from a CMJ or DJ-RSI are the most useful variables due to their sensitivity to fatigue. DJ-RSI has shown promise as a potential measure to indicate levels of fatigue given its apparent sensitivity following match play (Hamilton, 2009, Brownstein *et al.*, 2017, Thomas *et al.*, 2017). However, its sensitivity to fluctuations in training load and dose response relationship has yet to be established.

2.6.3 Accelerometer measures

The use of tri-axial accelerometers, such as those integrated into micro-electro-mechanical systems (MEMS), have demonstrated an ability to detect fatigue post exercise

(Patterson *et al.*, 2011, Cormack *et al.*, 2013). Indeed, exercise induced fatigue has been shown to result in an altered gait strategy during running (Patterson *et al.*, 2011), which has been associated with reduced sprint performance (Mendez-Villanueva *et al.*, 2008, Gathercole *et al.*, 2015), as well as increased injury risk (De Ste Croix *et al.*, 2015). Further, it has been shown that during a fatigue-inducing RS protocol, large decrements in accelerometer load, specifically vertical acceleration were observed (Akenhead *et al.*, 2017). The result of an altered running strategy are determined by a reduction in the vertical acceleration of the centre of mass during running (Lee and Farley, 1998). This has previously been detected by an integrated accelerometer worn between the scapula (Barrett *et al.*, 2014). In one of the first studies to assess tri-axial accelerometer load in team sports, Cormack et al., (2013) assessed players fatigue levels prior to a game, using the FT: CT ratio, and categorised them as fatigued or non-fatigued. They found a reduction in vertical acceleration in players categorised as fatigued, attributing these reductions to decrements in the force absorbing and generating capacity of the leg extensor muscles, which could potentially have implications for performance and injury risk (De Ste Croix *et al.*, 2015, Barrett *et al.*, 2016). More recently, Rowell *et al.* (2018) corroborated these findings by showing reduced FT: CT and reduced SSG output resulted in an increase in mediolateral acceleration and a decreased in vertical acceleration during match play. Although these data present clear changes in tri-axial accelerometer load during AFL match play, there is very limited research on the use of accelerometer data as a monitoring tool. One potential solution might be to utilise a sub-maximal running protocol which has been documented as widely used in practice (Akenhead and Nassis, 2016). This would allow for a timely assessment to be made, on a large squad of players, potentially as part of their daily warm-up. It is worth noting however, Edwards *et al.* (2018) and Verheul *et al.* (2019) suggest caution must be taken when using accelerometers within player tracking devices due to poor placement of the unit and an inability to measure whole body biomechanical load, this results in questionable validity and reliability of the data. Any future methods used to collect tri-axial accelerometer data should therefore ensue correct standardisation of the testing protocol and be clearly assessed for acceptable reliability.

2.6.4 Heart rate measures

The literature has focused upon the use of HR derived indices such as; HR_{ex}, and heart rate variability (HRV) as potential means of evaluating the effects of exercise on the cardiac autonomic nervous system (Buchheit, 2014, Thorpe *et al.*, 2017). The autonomic nervous system is interlinked with many other physiological systems (Borresen and Lambert, 2007), consequently, its responsiveness might provide useful information regarding global physiological status of a player during training and competition. Recent developments in technology that allow for non-invasive , beat-to-beat HR telemetry and more recently smart phone applications (Esco and Flatt, 2014) have advanced the application of HR measures in athletes (Buchheit, 2014). However, due to methodological inconsistencies within the literature, contradictory findings have been observed (Plews *et al.*, 2013, Buchheit, 2014).

Standardised sub-maximal tests have been used to assess HR_{ex}, which has been associated with changes in aerobic fitness (Buchheit, 2014). In AFL players Buchheit *et al.* (2013) found a *very large* inverse correlation between changes in high speed running performance (Yo-Yo IR1) and changes in HR_{ex}, indicating that chronic reductions in HR_{ex} are associated with improvements in fitness. However, changes in HR_{ex} also displayed a *large* inverse correlation with changes in training load, suggesting that increases in training load also reduce acute HR_{ex} (Buchheit *et al.*, 2013). This finding is in contradiction to what might be expected, for instance acute training-induced fatigue is generally associated with an increased sympathetic activity (Mourot *et al.*, 2004), which would suggest an increase in HR_{ex}. In elite football players HR_{ex} has been shown to remain unchanged across a training week, despite large fluctuations in training load (Thorpe *et al.*, 2016), this again questions the usefulness of HR_{ex} for assessing fitness and fatigue.

Vagal-related time domain parameters of HRV have recently received greater attention than more traditional spectral analyses due to their superior reliability and assessment capture over short periods of time (Malik *et al.*, 1996, Esco and Flatt, 2014, Thorpe *et al.*, 2017). Sensitivity to changes in training load and performance have mainly been observed in endurance athletes (Manzi *et al.*, 2009a). Commonly, HRV is reduced, indicating sympathetic dominance, in the days following intense exercise (Stanley *et al.*, 2013), however, results from endurance sports have shown inconsistent results (Plews *et al.*, 2014). In elite football, HRV has been shown to decrease in response to high-speed-running distance (r = 0.20) (Thorpe *et al.*, 2015). Contrastingly, in the same population, HRV did not change across a standard in-season training week (Thorpe *et al.*, 2016). Inconsistencies within the literature might be down to methodological differences, Plews et al. (2013, 2014) suggest measuring HRV daily on waking, and interpreting results in combination with resting HR to allow HRV saturation to be taken into consideration. Furthermore, the authors suggest the use of a rolling 7-day average to reduce the inherent noise in HRV data. Although the literature on the use of HR indices for monitoring the training response is theoretically sound, in applied practice, performing daily assessments with a squad of 20+ players might be difficult. Therefore further research is required to assess the efficacy of daily HR derived indices to assess the training response.

2.6.5 Endocrine measures

Previous literature has examined a range of endocrine measures; biochemical, hormonal and immunological responses to team-sport competition (Nédélec *et al.*, 2012, Twist and Highton, 2013). It is beyond the scope of this review to discuss the relevant literature on the vast number of endocrine responses to exercise. This section will specifically focus on four of the most popular endocrine measures; CK, salivary immunoglobulin A and cortisol. Changes in CK following match play have been discussed in Section 2.5.4, CK values peak between 24-48 h and return to baseline values from 72-120 h (Ispirlidis *et al.*, 2008, Magalhães *et al.*, 2010). Although widely used as a marker of muscle damage, questions remain regarding the apparent large individual variability (Hartmann and Mester, 2000) and between match variability (Russell *et al.*, 2015). Furthermore, no research to date has utilised CK measurement as a regular monitoring tool. Salivary immunoglobulin A has become a popular means to assess immune function in athletes via the use of real-time lateral flow devices. In elite football players salivary immunoglobulin A has shown reductions during an intensive fixture schedule (Morgans *et al.*, 2014). It could therefore be suggested that salivary immunoglobulin A provides a non-invasive assessment that is sensitive to the changes in either the physiological and/or psychological stress associated with a period of intensive training or competition. The adrenal hormone cortisol has been shown to increase up to 48 h after competition (Mohr *et al.*, 2016) and increase following period of intense training (Filaire *et al.*, 2003), indicating a stress response from the endocrine system during the recovery phase following match play. Very few longitudinal studies have assessed endocrine measures, particularly throughout a full football season. The impractical nature and cost of individual samples might explain the limited data assessing these measures over extended training and competition periods.

In summary this section has provided a brief review of the existing literature on methods for monitoring fatigue in football. Although a vast amount of literature exists on the time course of recovery post match, research on using such methods for daily or weekly monitoring of players is limited. The general consensuses within the literature is that measures must be cost effective, easy to administer, simple to analyse and help to inform the decision making process (Halson, 2014). Furthermore, the reliability, sensitivity and dose-response nature of a number of potential monitoring tools has yet to be evaluated and requires investigation.

2.7 Conclusion and Perspective

This review has provided a discussion of relevant literature on the physical and physiological demands of football, football training methodologies, fatigue in football and the monitoring of training load and fatigue, with special reference to the dose response relationship. Football is a highly demanding sport which requires an array of physical, physiological and cognitive capabilities in order to perform at the elite level. With these high physical and physiological demands comes a large amount of fatigue which can take a number of days to recover from. Furthermore, in order to train players to meet these demands comprehensive training regimes are required. The monitoring of training load and fatigue has become a critical aspect of the role of a practitioner within elite football. Careful daily monitoring is required to improve the training process, ensuring players are improving their physical capabilities without undue fatigue and increase injury risk. However, very limited research has been completed in this area. The dose-response relationship between training load, fitness and fatigue and how this impacts on physical performance in football is largely unknown. It is therefore the aim of this thesis to firstly, establish the most robust methods for monitoring fatigue in an applied environment. Secondly, to establish the relationship between training load, fitness and fatigue. And finally, to investigate how this relationship can be used to improve the monitoring and prescription of training and ultimately improve the physical performance of football players.

CHAPTER 3

3.0 GENERAL METHODOLOGY

3.1 Introduction

This chapter will provide a brief overview of the protocols that will be used to assess key variables throughout the thesis. Specifics relating to their application are contained within each individual chapter.

3.2 Ethical Approval

Institutional ethics approval was obtained from the University of Northumbria at Newcastle Faculty of Health and Life Sciences ethics committee in accordance with the Helsinki declaration. Prior to testing, all participants were provided with information sheets that described the purpose of each study. Written informed consent was provided by all participants and by their parents for participants under 18 years of age (see Appendix A). This research programme was conducted in collaboration with Newcastle United FC, an organisation at which I hold a professional position as Academy Sports Scientist. In order to maintain ethical and professional standards, club officials - Academy Manger and Head Coach, were informed of all the procedures of each study and they provided a written letter in support of this as part of each ethics approval submission.

3.3 Participants

All participants were volunteers from a full-time professional football academy competing in the English under 18 Premier League. Before inclusion in each study, participants were deemed to be free from illness and injury by the football club medical staff. All participants were familiarised with the experimental procedures prior to the completion of the initial experimental trials. Testing was conducted at the same venue within the clubs' training facility and were conducted at the same time of day to limit the influence of circadian variation.

3.4 Procedures

3.4.1 Fatigue measures

3.4.1.1 Subjective ratings of wellness

A psychometric questionnaire based on previous recommendations (Hooper and Mackinnon, 1995) was collected each day, on an electronic device, to assess common indicators of player wellness. In Chapters 4 and 5 questionnaire items were related to fatigue, sleep quality, muscle soreness, stress and mood. Each question was scored on a 5-point Likert scale with 1-point increments (scores of 1–5, with 1 and 5 representing very poor and very good, respectively) (Appendix B). Additionally, the summation of all 5 scores provided a total wellness score (5-25).

Due to the unacceptable reliability and sensitivity of the 5 item questionnaire reported in Chapters 4 and 5, the questionnaire was shortened in Chapter 6 to only include subjective fatigue, sleep quality and muscle soreness. Each question was scored on a 10-point Likert scale with 1-point increments (scores of 1–10, with 1 and 10 representing very poor and very good respectively) (Appendix C). Additionally, the summation of all 3 scores provided a total wellness score (3-30). Following the assessment of reliability and internal consistency in Chapter 6, only 2 items; subjective fatigue and muscle soreness were used in Chapters 7 and 8.

3.4.1.2 Jump assessments

Prior to completing assessments of jump performance a standardised warm up was completed. This consisted of three minutes, self-paced, light aerobic activity on a cycle ergometer (Keiser, Fresno, CA, USA), followed by dynamic mobility exercises and three submaximal practice CMJs. All jumps (described below) were completed using an optical timing system (OptoJump, Microgate, Italy), the validity of which has been previously established (Glatthorn et al., 2011). Each assessment consisted of four attempts, separated by one minute of rest. The average and the best of the four jumps were analysed during pilot testing and displayed very similar results. Therefore the average of the four jumps was used as the criterion measure of performance based on previous recommendations (Taylor et al., 2010).

Countermovement jump

The CMJ was executed to a self-selected depth, without pausing and the hands placed on the hips. Participants were instructed to jump as high as possible with no knee or hip flexion during the flight phase. Jump height (cm) estimated from flight time was recorded.

Squat jump

The squat jump (SJ) was executed to a self-selected depth with the hands placed on the hips (Figure 3.1). Participants were instructed to squat down to a self-selected depth for a four second count, then jump as high as possible with no knee or hip flexion during the flight phase. Jump height (cm) estimated from flight time was recorded.

Drop jump

The drop jump (DJ) was performed from a 30 cm box with hands placed on the hips, in line with previous research (Brownstein et al., 2017, Thomas et al., 2017). Participants were instructed to step off the box, rebound off the floor as quickly as possible and jump as high as possible with no knee or hip flexion (Figure 3.1). Contact time (ms) (DJ-CT), jump height (cm) estimated from flight time (DJ-H) and reactive strength index ($m \cdot s^{-1}$) (DJ-RSI) were recorded.

3.4.1.3 Sub-maximal shuttle run

A sub-maximal shuttle running test was used to assess participants' mechanical loading. All participants were fitted with a MEMS device (MinimaxX S4, Catapult Sports, Melbourne, Australia) worn between the scapular in a tight-fitting vest to reduce movement artefact. MEMS devices contained a tri-axial piezoelectric linear accelerometer (Kionix: KXP94) sampling at a frequency of 100 Hz. A continuous 20 m shuttle run was performed for a three minute period, at an average speed of 12 $km \cdot h^{-1}$, on an artificial 4G surface. Pacing was controlled using a custom audio track played over a loudspeaker. Data were downloaded using the manufacturer's software (Catapult Sprint, Version 5.1.7) and raw data were exported to Microsoft Excel. The first minute of data was discarded as a "stabilisation" period, the subsequent 2 minutes were used for statistical analysis. Combined tri-axial accelerometer data were presented as PL, which is a modified vector magnitude expressed as the square root of the sum of the squared instantaneous rates of change in acceleration in each of the three planes, divided by 100 (Boyd et al., 2011). Individual component planes of PL, anterior-posterior [PL_{AP}], mediolateral [PL_{ML}], and vertical [PL_{V}] were recorded and expressed in arbitrary units (au). The percentage contribution of each component plane to overall PL was also calculated; $\%PL_{AP}$, $\%PL_{ML}$ and $\%PL_{V}$.

Figure 3.1. Photographs showing examples of jump assessments. (Published with consent).

3.4.2 Physical performance testing

3.4.2.1 Maximum sprint speed

Following a standardised warm up, participants completed two maximal 40 m sprints on an artificial 4G surface, with three minutes recovery between efforts. Split times were recorded at 30 and 40 m (Brower Timing Systems, Draper, UT), with the time taken to complete this 10 m split used as the participants MSS ($km.h^{-1}$) (Mendez-Villanueva et al., 2013). The best MSS gained over the two sprints was used for the purpose of each study.

3.4.2.2 Maximal aerobic speed

To estimate MAS ($km.h^{-1}$) participants completed a 1500 m time trial on an outdoor artificial 4G pitch (Figure 3.2). The time taken to complete this time trial was recorded and the average speed calculated. This method of assessing aerobic fitness has previously been validated (Lorenzen et al., 2009, Bellenger et al., 2015). Additionally, ASR was calculated from this data by subtracting a players MAS from their MSS. This is in accordance with previous literature (Mendez-Villanueva et al., 2013).

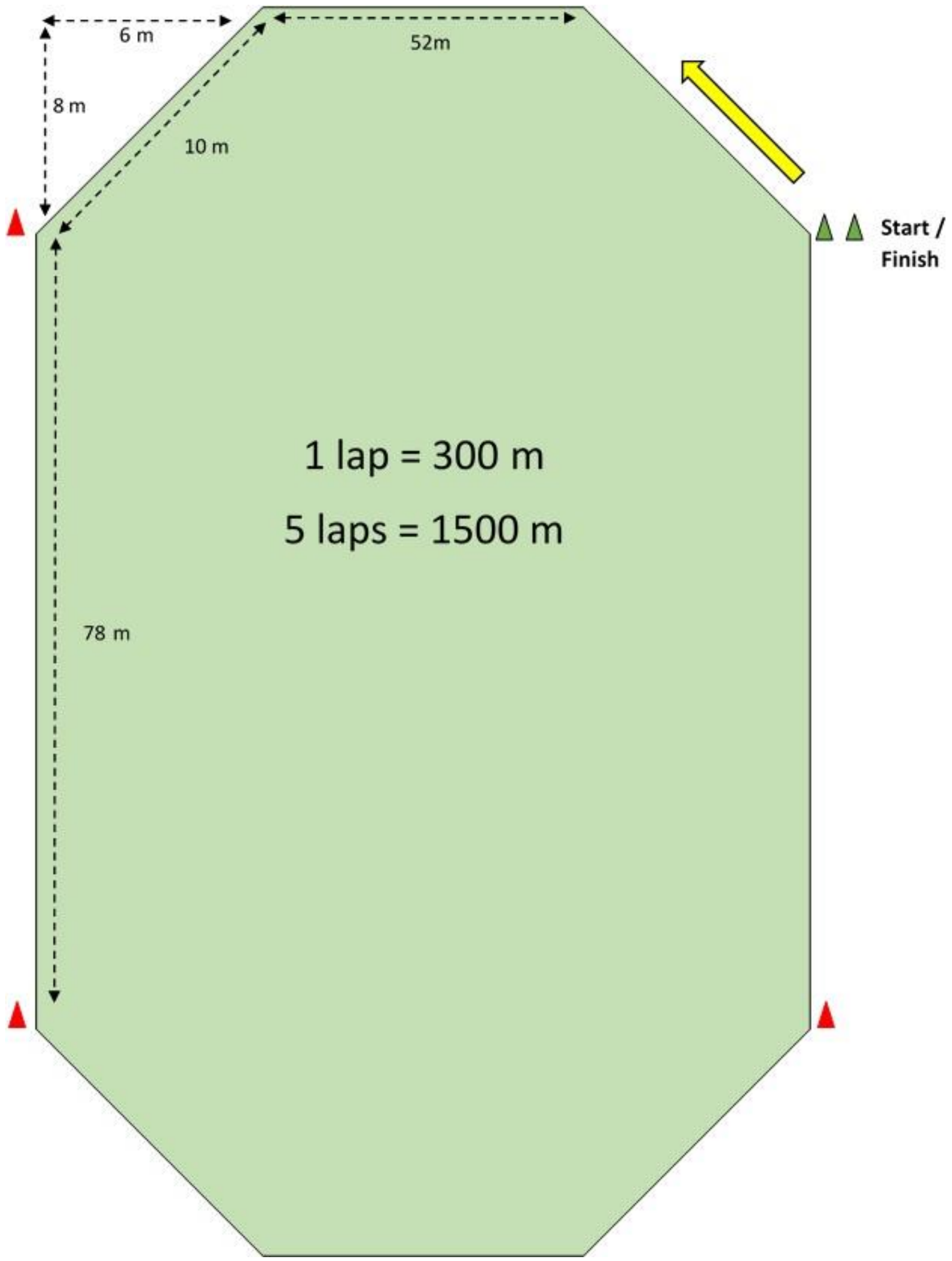

Figure 3.2. Schematic of the 1500m time trial completed on a 4G artificial football pitch.

3.4.3 Training load

Training load was calculated for every training session and match played during each experimental period, using a number of different methods; GPS, HR and sRPE.

3.4.3.1 Global positioning system

External load was measured using GPS units (MinimaxX S4, Catapult Sports, Melbourne, Australia) sampling at a frequency of 10 Hz. GPS devices were switched on at least 15 minutes prior to each training session and match to ensure a full satellite signal. Number of satellites (#sats) and horizontal dilution of precision (HDOP) values as described by Malone et al. (2017a), can be found in respective chapters. Participants were given the same device for each session to avoid inter-unit error (Jennings *et al.*, 2010). Following each training session and match, data were downloaded using the manufacturer's software (Catapult Sprint, Version 5.1.7, Catapult Sports, Melbourne, Australia). This GPS system has previously been shown to provide valid and reliable estimates of instantaneous velocity during acceleration, deceleration, and constant-velocity movements during linear, multidirectional, and football-specific activities (Varley *et al.*, 2012, Akenhead *et al.*, 2014). A description of external load variables can be found in Table 3.1.

Table 3.1. Description of external training load variables gained via global positioning system technology.

TD	Total distance covered in training or match play
HSR	Distance covered or time spent above 17 $km \cdot h^{-1}$
VHSR	Distance covered or time spent above 21 $km \cdot h^{-1}$
SPR	Distance covered or time spent above 24 $km \cdot h^{-1}$
AD Load	Acceleration and deceleration distance ± 2 $m \cdot s^{-2}$
MAS	Distance covered or time spent above MAS $km \cdot h^{-1}$
30% ASR	Distance covered or time spent above 30% ASR $km \cdot h^{-1}$

Note: TD: total distance, HSR: high speed running, VHSR: very high speed running, SPR: sprint running, AD Load: acceleration and deceleration load, MAS: maximal aerobic speed, ASR: anaerobic speed reserve.

3.4.3.2 Heart rate telemetry

Measurements of HR were collected using a short-range telemetry HR transmitter strap recording at 5 s intervals (Polar T34, Polar Electro, OY, Finland). Data were downloaded and analysed using specific software (Catapult Sprint, Version 5.1.7, Catapult Sports, Melbourne, Australia). A heart rate exertion (HRE) score was calculated based on Edwards TRIMP (Edwards, 1993), using the time spent in five HR zones, based on age-predicted HR_{max} (Tanaka *et al.*, 2001) and multiplied by a zone specific weighting factor: duration in zone one (50-59% of HR_{max}) multiplied by one, duration in zone two (60-69% HR_{max}) multiplied by two, duration in zone three (70-79% HR_{max}) multiplied by three, duration in zone four (80 89% HR_{max}) multiplied by four and duration in zone five (90-100% HR_{max}) multiplied by five.

3.4.3.3 Session rating of perceived exertion

Approximately 30 minutes after each training session and match, participants reported their RPE using the method of Foster et al (1996). Each player was asked verbally, in private, how hard they found each session, reporting their subjective perception of effort using the Borg 10-point scale. sRPE was subsequently calculated by multiplying the RPE by the number of training or match minutes played. Participants were familiarised with the use of the RPE scale prior to the start of each experimental period.

3.4.4 Standardised training session

A standardised training session was used regularly throughout this thesis in order to assess a training induced fatigue response (Chapters 5, 6 and 7). Although the sessions varied slightly between chapters, the sessions completed within each chapters were always standardised and typically included a warm up, possession drills, technical and tactical drills, SSGs and supplementary running drills. This session was designed based on previous unpublished observations as to what a "strenuous" training session would entail given the playing standard, and training age of the participants.

An example of a standardised session training load report can be found in Appendix D. When training load was manipulated in Chapter 6 – Part I to establish the dose-response relationship the main body of the session was standardised with varying levels of supplementary running completed in order to provide a "moderate", "high" or "very high" training load. Specific details about the standardised training sessions and training loads can be found within each individual chapter.

CHAPTER 4

4.0 THE RELIABILITY OF POTENTIAL FATIGUE MONITORING MEASURES IN ELITE YOUTH FITNESS PLAYERS

Published papers from this chapter:

Fitzpatrick, J. F., Russell, M., Hicks, K. M. and Hayes, P. R. (2019) The reliability of potential fatigue monitoring measures in elite youth soccer players. *The Journal of Strength and Conditioning Research*, Published ahead of print.

Conference communications from this chapter:

Fitzpatrick, J. F., Russell, M. and Hayes, P. R. (2016). Reliability of a fatigue response in elite youth football players. *21st annual Congress of the European College of Sport Science*, Vienna, Austria, 6^{th} – 9^{th} July 2016.

4.1 Introduction

In sport, the ability to monitor and manage training and fatigue is of vital importance to coaches and practitioners (Halson, 2014). In an attempt to make informed decisions about physical performance, fatigue status, readiness to train and training prescription, practitioners seek methods that attempt to quantify the magnitude of fatigue throughout the competitive week (McCall *et al.*, 2014, Akenhead and Nassis, 2016). As discussed within the literature review of this thesis, many methods exist to monitor fatigue in an applied setting; subjective wellness measures, physical performance tests, autonomic nervous system function and biochemical markers to name a few (Twist and Highton, 2013, Halson, 2014, Thorpe *et al.*, 2017). Concerns about reliability and logistical feasibility however, might prevent the use of such methods being used on a regular basis, in practice (Akenhead and Nassis, 2016).

An important factor to consider when selecting a potential measure of fatigue is measurement reliability. The reliability of a test refers to an acceptable level of consistency between repeated tests within a practically relevant timeframe (Atkinson and Nevill, 1998). A test with poor reliability will be unsuitable for tracking changes in fatigue due to an inability to detect a true change in the measure (Hopkins, 2000). Factors that influence reliability include the protocol, measurement device used to collect the data and any systematic or random changes in the mental or physical state of the individual between trials (Atkinson and Nevill, 1998, Hopkins, 2000). It is therefore imperative that practitioners understand the error associated with the measures they use in practice, something which is lacking within the literature.

Subjective measures are widely used in team sports (Taylor *et al.*, 2012a, Akenhead and Nassis, 2016), however there has yet to be a consensus on the most appropriate questionnaire to be used. Profile of Mood States (McNair *et al.*, 1981), Recovery-Stress

Questionnaire (Kellmann and Kallus, 2001) and Daily Analyses of Life Demands (Rushall, 1990) are just some of the assessment tools which have been used within the literature. However, their length, narrow focus or lack of specificity to the sporting context has led many sports programs to develop their own questionnaires (Saw *et al.*, 2015a). Subsequently, practitioners and researchers have incorporated customised, shortened questionnaires into their monitoring practices and research (Hooper and Mackinnon, 1995, McLean *et al.*, 2010). However, the reliability and sensitivity of these shortened wellness questionnaires has yet to be established. In contrast, the reliability of assessments of jump performance are well established, with reported coefficient of variations (CV) of 5% for CMJ (Cormack *et al.*, 2008b), 3% for the SJ (Glatthorn *et al.*, 2011) and 5-8% for variables derived from a DJ (Beattie and Flanagan, 2015). However, no studies have documented the minimum detectable change (MDC) which might represent a more appropriate measure of reliability, providing practitioners with important information about what change can be considered real (Weir, 2005). The MDC will provide a level of confidence that a real change had occurred. Furthermore, the MDC factors in the error of both trail 1 and trail 2, something that is highly important when assessing test retest reliability.

A recent survey showed that 61% of elite European football teams regularly use a sub-maximal, non-exhaustive performance test to assess autonomic function (Akenhead and Nassis, 2016). However, research suggests that due to the limited sensitivity of HR measures this approach might offer limited meaningful information (Thorpe *et al.*, 2015, Thorpe *et al.*, 2016). Notwithstanding issues with reliability, validity and sensitivity, a possible solution might be to utilise other data streams that can be collected during a sub-maximal assessment. The use of tri-axial accelerometers, such as those integrated into MEMS devices, have demonstrated an ability to detect fatigue post exercise (Patterson *et al.*, 2011), with vertical acceleration showing changes under fatigue during both match-play (Cormack *et al.*, 2013) and training (Rowell *et al.*, 2018).Furthermore, Buchheit et al. (2015a) assessed the reliability of stride variables derived from MEMS devices during treadmill running. They found that measures of contact time, fight time and vertical stiffness have a good to moderate reliability (4-16% CV). These data give preliminary insights into the ability of tri-axial accelerometer data to display changes under fatigue, however the reliability of measures derived from MEMS devices during sub-maximal field tests has yet to be established. Furthermore, there is no evidence within the literature as to the duration of a sub-maximal test required to gain reliable data. This has important implications for practitioners as a shorter test duration is likely to improve compliance in an applied setting.

A second aspect of this chapter was to assess the reliability of potential measures of physical performance, specifically MAS and MSS. As highlighted during Chapter 2, the aerobic fitness and sprint capabilities of football players are highly important qualities to assess (Mendez-Villanueva and Buchheit, 2013). Not only can these measures be used to assess physical performance, they can also be used to individualise training load (Hunter *et al.*, 2015) and inform high intensity interval training (Dupont *et al.*, 2004). If reliable, these measures will be used extensively in Chapters 7 and 8, therefore examining the test re-test reliability and MDC were of upmost importance in this study.

Previous literature has established the reliability of MSS using the popular method of a flying 10 m time from a 40m sprint (Buchheit and Mendez-Villanueva, 2013). However, the MDC has yet to be established, therefore, in order to maintain consistency throughout this thesis the assessment of MSS test re-test reliability was completed. To assess MAS, the gold standard method would be to evaluate speed at maximum oxygen uptake ($s\dot{V}O_{2max}$). This is the maximum running speed attained for at least one minute before completion of the incremental treadmill test (Billat and Koralsztein, 1996). Obtaining

$s\dot{V}O_{2max}$ is, however, labour intensive and time consuming. An indirect alternative is mean running speed calculated from a time trial (Slattery *et al.*, 2006). This method of assessment is easier, quicker, and more cost effective than laboratory testing and therefore, if reliable, might provide a sound, more practical assessment of MAS (Lorenzen *et al.*, 2009). Estimation of MAS based on short distance time trial performance is conceivable since time trails require maximal efforts demanding a high contribution of aerobic power, which MAS is claimed to measure (Leger and Boucher, 1980). Previous research has shown that distances between 1500 m and 3200 m can be used to accurately estimate MAS (Lorenzen *et al.*, 2009, Bellenger *et al.*, 2015). For the purpose of this study a 1500 m time trial was selected. The rationale for this was to limit the volume of testing to fit around the players training and match schedule.

Establishing the reliability of measures used to monitor athletes physical performance and fatigue status is an imperative aspect of applied research and practice. Further, field-based, *in situ* reliability assessments are required in order to quantify "real" changes in these measures in athletes within their normal training environment and across time periods that are typically used to quantify the effects of any intervention (Atkinson and Nevill, 1998).

4.1.1 Study aims

The aim of this study was to quantify the test re-test reliability of a subjective wellness questionnaire, assessments of jump performance and accelerometer variables derived during sub-maximal shuttle running in elite youth football players. Also, this study looked to assess the reliability of a 40 m sprint test to assess MSS and a 1500 m time trial to assess MAS and establish thresholds for what can be considered "real" changes in these measures.

4.2 Methods

4.2.1 Study design

This study was completed at the beginning of the 2015-16 season (October) and consisted of two testing sessions spaced seven days apart. All players were in full training during the study, completing around 10.5 h per week of pitch (8.5 h) and gym (2 h) based activity. All players were familiarised with the experimental procedures prior to commencing the study, having completed these assessments regularly as part of the football clubs testing procedures. Each testing session consisted of morning ratings of subjective wellness, three different assessments of jump performance; CMJ, SJ and DJ and a sub-maximal shuttle run test used to assess accelerometer variables, in respective order. On a separate occasion 40 m sprints and a 1500 m time trail were completed to assess MSS and MAS. Training load was monitored carefully throughout the study period to ensure limited differences between training weeks (sRPE; Week 1 = 2247, Week 2 = 2280, CV = 9.9%). Both testing sessions were preceded by 48 h of rest and were conducted at the same time of day to limit the influence of possible circadian variation.

4.2.2 Participants

Nineteen male youth football players (Age: 17.2 ± 0.5 years, Height: 176.4 ± 4.9 cm, Body Mass: 73.1 ± 8.5 kg), competing in the English Under-18 Premier League volunteered to participate in this study. Participants were given full details of the study procedures and provided personal, and when under 18, parental/guardian written consent before participation. Institutional ethical approval was gained prior to any study involvement (HLSJF240415). Prior to inclusion in the study, all participants were deemed fit to participate and free of illness or injury by the football club's medical staff.

4.2.3 Procedures

4.2.3.1. Subjective wellness

A 5-item questionnaire to assess subjective ratings of fatigue, sleep quality, muscle soreness, stress and mood were collected as described in Chapter 3, Section 3.4.1.1.

4.2.3.2 Jump performance

Jump performance was assessed for a CMJ, SJ and DJ. Data were collected as described in Chapter 3, Section 3.4.1.2.

4.2.3.3 Sub-maximal shuttle running

A sub-maximal shuttle run was conducted as described in Chapter 3, Section 3.4.1.3. For this chapter the test was conducted for a period of five minutes. The first minute of data was discarded as a stabilisation period, the subsequent two, three and four minutes of the collection period were used for statistical analysis. This was to compare the reliability of different time periods and identify the minimum test duration which can be used to reliably collect accelerometer data during sub-maximal shuttle running.

4.2.3.4 Maximum sprint speed

A 40 m sprint test was used to assess MSS as described in Chapter 3, Section 3.4.2.1.

4.2.3.5 Maximal aerobic speed

A 1500 m time trial was conducted to assess MAS as described in Chapter 3, Section 3.4.2.2.

4.2.4 Statistical analysis

Visual inspection of histograms and Q–Q plots of raw data indicated no violation of normality assumptions. Raw data are therefore presented as the mean ± standard deviation (SD). Test re-test reliability was calculated for each variable and expressed as a typical error (TE), CV and interclass correlation (ICC), calculated using a custom spreadsheet (Hopkins, 2015). To assess the ability of each variable to assess "real" change the MDC (75% confidence level) was also calculated (Weir, 2005). This measures provides a more stringent assessment of error as it provides a 75% confidence level around the TE and multiples by $\sqrt{2}$ to factor in the error in both the pre and post assessment. The MDC was then used as an input in statistical power calculations to estimate whether the random measurement error would be small enough to detect the MDC in each outcome measure with a feasible sample size in a future study (Batterham and Atkinson, 2005). Finally, to evaluate the internal consistency of the subjective wellness questionnaire Cronbach's Alpha (α) was calculated (Cronbach, 1951), with a threshold of >0.7 being set for an acceptable α (Bland and Altman, 1997), finally, inter-item correlations were considered.

4.3 Results

4.3.1 Subjective wellness

Reliability statistics for each subjective wellness measure are shown in Table 4.1. The TE for individual subjective wellness questions ranged from 0.30 to 0.60 and was 1.59 for total wellness. When expressed as a CV values ranged from 11.2% to 30.0%. ICCs for subjective wellness measures ranged from -0.01 to 0.78. The MDC for each subjective wellness measure is displayed in Table 4.1, power estimations suggest a sample size of 9 players would be deemed acceptable for future studies. As an additional measure of reliability for the questionnaire, Cronbach's α was assessed, this analysis resulted in α =

0.45 meaning the internal consistency of the 5-items within this subjective wellness questionnaire is poor. Further analysis into the inter-item correlations showed poor relationships, with the only substantial correlation being between stress and mood items.

4.3.2 Jump performance

Reliability statistics for each jump test are shown in Table 4.2. The TE for CMJ, SJ and DJ-H was 1.6 cm, 1.5 cm and 1.8 cm respectively. When expressed as a CV these values were 4.8%, 4.5% and 6.0% respectively. The TE and CV for DJ-CT was 0.01 s and 4.9% and for DJ-RSI was 0.11 and 7.7%. ICCs for the jump assessments ranged from 0.76 to 0.88. The MDC for each jump test is displayed in Table 4.2, power estimations suggest a sample size of 9-10 players would be deemed acceptable for future studies.

4.3.3 Sub-maximal shuttle run

A summary of reliability statistics for the accelerometer data from two minutes of analysis for the sub-maximal shuttle run is shown in Table 4.3. Reliability was consistent across all analysis time frames (2, 3 and 4 minutes). ICCs for each accelerometer variable across all time frames ranged from 0.63 to 0.96. The MDC for each accelerometer variable is displayed in Table 4.3, power estimations suggest a sample size of 9-10 players would be deemed acceptable for future studies.

4.3.4 Maximum sprint speed and maximal aerobic speed

Reliability statistics for MSS and MAS are shown in Table 4.4. Both MSS and MAS showed very good reliability. The MDC values for each measure are also displayed in

Table 4.4, power estimations suggest a sample size of 9 players would be deemed acceptable for future studies.

Table 4.1. Reliability statistics for subjective wellness measures.

	Trial 1 (SD)	Trial 2 (SD)	TE (90% CI)	ICC (90% CI)	CV (%) (90% CI)	MDC	MDC (%)	Required Sample Size
Fatigue (au)	3.2 *(0.5)*	3.1 *(0.7)*	0.3 *(0.2, 0.4)*	0.78 *(0.56, 0.90)*	14.9 *(11.4, 21.8)*	0.5	14.9%	9
Sleep Quality (au)	3.8 *(0.5)*	3.6 *(0.6)*	0.6 *(0.5, 0.8)*	-0.01 *(-0.41, 0.39)*	21.0 *(16.1, 31.1)*	0.9	24.9%	9
Muscle Soreness (au)	3.0 *(0.9)*	2.7 *(0.8)*	0.6 *(0.5, 0.9)*	0.54 *(0.17, 0.77)*	30.0 *(22.7, 45.1)*	0.9	33.3%	9
Stress (au)	3.4 *(0.7)*	3.1 *(0.9)*	0.6 *(0.5, 0.8)*	0.46 *(0.08, 0.73)*	22.7 *(17.3, 33.6)*	0.9	28.9%	9
Mood (au)	3.9 *(0.6)*	3.9 *(0.7)*	0.6 *(0.5, 0.8)*	0.15 *(-0.27, 0.52)*	19.2 *(14.7, 28.2)*	0.9	24.2%	9
Total Wellness (au)	17.3 *(1.9)*	16.5 *(2.0)*	1.6 *(1.2, 2.3)*	0.35 *(-0.06, 0.66)*	11.2 *(8.6, 16.2)*	2.5	15.0%	9

Data are presented as group means (± SD) for each trial, typical error (TE), interclass correlation (ICC), coefficient of variation (CV), and minimum detectable change (MDC) (75% confidence level). The required sample size represented 80% power to detect the MDC.

Table 4.2. Reliability statistics for jump tests; countermovement jump height (CMJ), squat jump height (SJ), drop jump contact time (DJ-CT) drop jump height (DJ-H) and drop jump reactive strength index (DJ-RSI).

	Trial 1 (SD)	**Trial 2 (SD)**	**TE (90% CI)**	**ICC (90% CI)**	**CV (%) (90% CI)**	**MDC**	**MDC (%)**	**Required Sample Size**
CMJ (cm)	35.3 *(4.5)*	35.0 *(4.0)*	1.6 *(1.3, 2.3)*	0.88 *(0.73, 0.94)*	4.8 *(3.7, 6.9)*	2.5	7.0%	9
SJ (cm)	34.7 *(4.3)*	34.4 *(3.8)*	1.5 *(1.2, 2.1)*	0.88 *(0.75, 0.95)*	4.5 *(3.5, 6.4)*	2.3	6.6%	9
DJ-CT (ms)	0.20 *(0.02)*	0.21 *(0.02)*	0.01 *(0.01, 0.01)*	0.85 *(0.69, 0.93)*	4.9 *(3.8, 7.0)*	0.01	7.2%	9
DJ-H (cm)	29.8 *(3.5)*	29.9 *(3.4)*	1.8 *(1.4, 2.5)*	0.76 *(0.51, 0.89)*	6.0 *(4.6, 8.6)*	2.8	9.2%	9
DJ-RSI ($m.s^{-1}$)	1.49 *(0.23)*	1.43 *(0.23)*	0.11 *(0.08, 0.15)*	0.80 *(0.59, 0.91)*	7.7 *(6.0, 11.1)*	0.16	10.9%	10

Data are presented as group means (± SD) for each trial, a typical error (TE), interclass correlation (ICC), coefficient of variation (CV), and minimum detectable change (MDC) (75% confidence level). The required sample size represented 80% power to detect the MDC.

Table 4.3. Reliability statistics for PlayerLoad™ (PL), individual component planes; anterior-posterior (PL_{AP}), mediolateral (PL_{ML}), and vertical (PL_{V}), and the percentage contribution of each plane.

	Trial 1 (SD)	**Trial 2 (SD)**	**TE (90% CI)**	**ICC (90% CI)**	**CV (%) (90% CI)**	**MDC**	**MDC (%)**	**Required Sample Size**
PL	39.6 *(3.8)*	39.5 *(3.6)*	0.9 *(0.7, 1.4)*	0.95 *(0.87, 0.98)*	2.4 *(1.8, 3.5)*	1.4	3.5%	10
PL_{AP}	14.8 *(2.3)*	14.5 *(2.5)*	1.1 *(0.9, 1.6)*	0.81 *(0.59, 0.92)*	8.0 *(6.1, 11.8)*	1.7	11.6%	9
PL_{ML}	14.4 *(2.0)*	13.9 *(1.9)*	0.7 *(0.5, 1.0)*	0.89 *(0.74, 0.95)*	5.7 *(4.4, 8.5)*	1.1	7.5%	9
PL_{V}	28.1 *(3.1)*	28.1 *(3.0)*	0.9 *(0.7, 1.3)*	0.93 *(0.84, 0.97)*	3.2 *(2.5, 4.8)*	1.3	4.6%	10
$\%PL_{AP}$	25.8% *(3.0%)*	25.6% *(2.7%)*	1.8% *(1.4%, 2.6%)*	0.63 *(0.28, 0.83)*	7.2 *(5.5, 10.6)*	2.8%	10.8%	9
$\%PL_{ML}$	25.2% *(2.8%)*	24.6% *(3.1%)*	1.3% *(1.0%, 1.9%)*	0.83 *(0.63, 0.93)*	5.9 *(4.5, 8.7)*	2.0%	7.9%	9
$\%PL_{V}$	49.0% *(2.8%)*	49.8% *(2.9%)*	1.3% *(1.0%, 1.9%)*	0.83 *(0.62, 0.93)*	2.7 *(2.0, 3.9)*	2.0%	3.9%	6

Data are presented as group means (± SD) for each trial, typical error (TE), interclass correlation (ICC), coefficient of variation (CV), and minimum detectable change (MDC) (75% confidence level). The required sample size represented 80% power to detect the MDC.

Table 4.4. Reliability statistics for measures of maximum sprint speed (MSS) and maximal aerobic speed (MAS).

	Trial 1 (SD)	**Trial 2 (SD)**	**TE (90% CI)**	**ICC (90% CI)**	**CV (%) (90% CI)**	**MDC**	**MDC (%)**	**Required Sample Size**
MSS ($km.h^{-1}$)	32.1 *(1.4)*	31.7 *(1.5)*	0.4 *(0.3, 0.6)*	0.93 *(0.84, 0.97)*	1.4 *(1.1, 1.9)*	0.7	2.0%	9
MAS ($km.h^{-1}$)	17.2 *(0.9)*	17.6 *(0.8)*	0.2 *(0.1, 0.2)*	0.97 *(0.93, 0.99)*	1.0 *(0.8, 1.4)*	0.3	1.5%	9

Data are presented as group means (± SD) for each trial, typical error (TE), interclass correlation (ICC), coefficient of variation (CV), and minimum detectable change (MDC) (75% confidence level). The required sample size represented 80% power to detect the MDC.

4.4 Discussion

The aim of the present study was to quantify the test re-test reliability of a range of potential measures of fatigue and physical performance in a group of elite youth football players. The key findings from this study were: (1) a short 3 minute (2 minute analysis) sub-maximal shuttle run from which accelerometer data was collected showed good reliability, (2) good reliability was shown for a number of jump assessments; CMJ, SJ, DJ-CT and DJ-RSI, (3) the psychometric questionnaire used to assess subjective wellness showed poor reliability and poor internal consistency, (4) very good reliability was shown for all measures of physical performance.

A novel aspect within this study was the use of a sub-maximal test to assess accelerometer data gained during shuttle running. All variables displayed consistent reliability statistics across all time frames. These results are in accordance with recent research which assessed the validity and reliability of measures of vertical stiffness and peak loading forces collected via GPS-embedded accelerometers during treadmill running, and found good to moderate reliability (4-16% CV) (Buchheit *et al.*, 2015b). However, the measures used in the aforementioned study require specialist software for analysis that utilises proprietary detection algorithms to recognize foot strikes, a method that has recently been questioned (Cust *et al.*, 2018). Furthermore, these variables are not widely available to practitioners using manufacturer software, therefore the data presented in the present study might provide a more practical alternative. This is the first study to assess these variables during a sub-maximal field test that can easily be completed as part of the players' daily or weekly training regime. A secondary aim of this study was to assess the minimum test duration that could maintain good reliability. A three minute assessment, from which the first minute is discarded as a stabilisation period and the final two minutes used for analysis, is shown to be an acceptable time frame. This provides a clear guideline for practitioners who might want to assess a large squad of players simultaneously in a small period of time; for example as part of a pre-training warm-up.

The assessment of fatigue via jump performance measures, such as, CMJ, SJ and DJ represents a popular method by which to monitor players in the field. A survey of 41 elite European football teams indicated that 39% utilise a form of jump testing on a weekly basis to monitor fatigue (Akenhead and Nassis, 2016). Due to their popularity a number of studies have assessed the test re-test reliability of jump assessments, however, it was important to examine the reliability in the specific environment and cohort which would be used throughout this thesis. Findings from the present study indicate good reliability for all jump measures, however DJ-H did display the lowest ICC out of all. The reduced reliability of DJ-H might be due to the high skill demand of the DJ, however, all players were familiarised with the test before completing the present study. These results are in agreement with previous observations that have reported a CV of 5% for CMJ height (Cormack *et al.*, 2008b), 3% for SJ height (Glatthorn *et al.*, 2011) and 5-8% for variables derived from a DJ (Beattie and Flanagan, 2015). An important consideration when reviewing the literature on reliability of jump assessments is the range of testing modalities used (contact mats, force platforms and photoelectric technology). The present study used the OptoJump system which has previously shown good reliability and validity when assessing CMJ and SJ (Glatthorn *et al.*, 2011). This is the first study to document the reliability of a DJ assessed via the OptoJump system, which provides a relatively cost effective and portable solution for testing in the field compared to force platforms. Alongside, the CV and ICC another key reliability statistic is the MDC. For jump measures the MDC ranged from 6.6 - 10.9 %, this provides important information for subsequent chapters in this thesis and for practitioners. Emphasising that changes in jump performance need to be greater than or equal to the MDC for a change in that measure to be considered real.

In the present study all individual subjective wellness items and overall total wellness displayed somewhat poor reliability. These findings suggest that if using the current subjective wellness questionnaire, tracking changes in fatigue on a week to week basis might be difficult. To our knowledge, this is the first study to examine the reliability of this type of short psychometric questionnaire that is regularly used in the applied environment. Other, larger questionnaires such as the Recovery-Stress questionnaire (76-questions) have shown large test re-test correlations ($r = 0.79$) (Kellmann and Kallus, 2001). The factor/s mediating the poor reliability found in the present study might be due to the simplicity of the questionnaire used. The categorical nature of a 5-point Likert style question means a 1 point change, e.g. from 5 to 4, is the equivalent to a 20% decrease.

Another aspect of reliability of a psychometric questionnaire is the internal consistency. This was assessed via Cronbach's α, with results indicating that the internal consistency of this questionnaire is poor. This has implications for the composite total wellness score which is the summation of all five questions. As each item has relatively low inter-item correlations it could be suggested that a composite score for total wellness should be used with caution. Future research should look to amend which items are included in the composite score in order to improve the internal consistency. Given the high CV and low ICC of each variable, and the poor internal consistency, in order to make this subjective wellness questionnaire more reliable and robust in an applied environment the low categorical nature of the Likert scale should be addressed. Conceivably, by increasing the number of points within the scale to 10, this would provide more options for players to select and therefore decrease the magnitude of a one unit change.

Another aim of this chapter was to establish the reliability of physical performance measures, specifically MSS and MAS. The reliability of MSS was shown to be very good, this is in line with other studies that have assessed MSS in Under-18 football players using a 10 m split time from a 40 m sprint (Buchheit and Mendez-Villanueva, 2013). Similarly, the reliability of MAS was very good. This is the first study to document the test re-test reliability of a 1500 m time trial in a cohort of elite youth football players. Furthermore, the MDC provided in Table 4.4 provides practitioners with thresholds for what can be considered “real” changes in physical performance measures. These are important findings for future chapters within this thesis, the excellent reliability shown for MSS and MAS allows us to confidently use these measures to individualised external training load in Chapter 6. Further, the MDC calculated will allow accurate inferences about any performance improvements to be made during Chapter 7.

4.4.1 Conclusion

In conclusion, this study has established good reliability for CMJ, SJ and DJ variables. Accelerometer data gained during sub-maximal shuttle running also displayed good reliability during a short three minute assessment. However, results suggest that subjective wellness assessed via a short 5-item psychometric questionnaire has poor test re-test reliability and internal consistency, therefore, caution must be taken when assessing changes in subjective wellness as an indicator of a players fatigue status. Furthermore, physical performance measures of MSS and MAS exhibited excellent test re-test reliability. The MDC calculated for all measures provides thresholds for “real” change, allowing accurate decisions to be made about the magnitude of change in subsequent chapters.

4.5 Perspective

Chapter 2 of this thesis examined the current literature and provided a discussion of commonly used methods to monitor fatigue in an applied football environment. It became clear that although a number of different methods are used the reliability of certain measures has yet to be established.

Chapter 4 has therefore established the test re-test reliability of a number of potential fatigue measures, which were appropriate for the environment in which this program of research was carried out.

Chapter 4 concluded that various jump tests and accelerometer variables have good reliability. However, the short 5-item wellness questionnaire showed poor reliability and internal consistency. Irrespective of the level of reliability it is important to discussion these measure in the context of measurement “signal” and “noise”. By calculating the MDC for each variable a clear benchmark for measurement “noise” has been established. Chapter 5 will attempt to build upon these findings and establish firstly, the sensitivity of a fatigue response following a standardised training session, and secondly, the reproducibility of this response. This will provide us with a clear benchmark for measurement “signal”. Only once we have an understanding of both signal and noise can we make a decision about the usefulness of a particular measure of fatigue or physical performance.

CHAPTER 5

5.0 SENSITIVITY AND REPRODUCIBILITY OF A FATIGUE RESPONSE IN ELITE YOUTH FOOTBALL PLAYERS

Published papers from this chapter:

Fitzpatrick, J. F., Akenhead, R., Russell, M., Hicks, K. M. and Hayes, P. R. (2019) Sensitivity and reproducibility of a fatigue response in elite youth football players, *Science and Medicine in Football*, 3:3, 214-220.

Conference communications from this chapter:

Fitzpatrick, J. F., Russell, M. and Hayes, P. R. (2016). Reliability of a fatigue response in elite youth football players. *21st annual Congress of the European College of Sport Science*, Vienna, Austria, 6^{th} – 9^{th} July 2016.

5.1 Introduction

Team sport activity has been shown to elicit fatigue commensurate with performance decrements and increased injury risk in youth and senior players (Mohr *et al.*, 2005, Rampinini *et al.*, 2011). In an attempt to make informed decisions about fatigue status, readiness to train and training prescription, applied practitioners seek methods that attempt to quantify the magnitude of fatigue throughout the competitive week (Halson, 2014, McCall *et al.*, 2014, Akenhead and Nassis, 2016). Chapter 4 of this thesis documented the test re-test reliability and thresholds for MDC associated with a number of jump assessments, accelerometer variables and subjective wellness measures, providing a clear estimate of measurement "noise". However, the sensitivity (signal) of these measures to training and/or match-play induced fatigue needs to be established. Measures of fatigue can only be considered valid if they show substantial sensitivity to changes in training load on a consistent basis.

Surveys on fatigue monitoring in high performance sport demonstrate that subjective wellness monitoring is used extensively for assessing the overall well-being of team sport athletes (Taylor *et al.*, 2012b). With 78% of elite football clubs stating they use these measures on a daily, weekly or monthly basis (Akenhead and Nassis, 2016). A recent review highlighted that subjective monitoring identified impaired wellness with acute increases in training load, and improved wellness with an acute reduction in training load (Saw *et al.*, 2015b). Furthermore, subjective measures responded with superior sensitivity and consistency compared to objective measures, such as endocrine or HR measures (Saw *et al.*, 2015b, Thorpe *et al.*, 2015). Daily subjective wellness has been shown to correlate with daily fluctuations in training load, indicating a possible dose-response relationship (Thorpe *et al.*, 2015, Scott and Lovell, 2017). Despite this body of evidence suggesting subjective wellness questionnaires are able to detect acute changes in fatigue Chapter 4 concluded that they have poor test re-test reliability. Therefore, the present study will use the MDC calculated in Chapter 4 to assess whether, in spite of poor reliability, subjective wellness measures are able to detect a fatigue response greater than the MDC.

A range of jump tests; CMJ, SJ and DJ, have been used to examine the time course of decrements in physical performance following football match-play, with reductions in jump performance reported for up to 72 h (Nédélec *et al.*, 2012). Brownstein *et al.* (2017) found decrements in CMJ height and DJ-RSI immediately post match play and at 24 h before recovering at 48 h post. Additionally, they found a substantial relationship between CMJ height and motor point voluntary activation, indicating that central mechanisms of neuromuscular function might be the cause of the decrements in CMJ height. However, the sensitivity of jump tests to changes in training load remain unclear. In football players, CMJ was not sensitive as a measure of fatigue when analysed alongside daily fluctuations in training load, displaying a weak dose-response relationship ($r = 0.23$) (Thorpe *et al.*, 2015). It has been suggested that jump height might not be a sensitive measure due to changes in jump strategy in an attempt to maintain jump height, which might mask the effects of fatigue (Gathercole *et al.*, 2015). Other force-time variables such as the FT: CT ratio (Cormack *et al.*, 2008b) or DJ-RSI (Hamilton, 2009) have displayed a sensitivity to acute changes in training load and therefore might offer a more appropriate measure of fatigue than CMJ height. Similar to subjective wellness however, no research to date has established if assessments of jump performance can detect a reproducible fatigue response in football players. Therefore, given the reliability established in Chapter 4; CMJ, SJ and DJ-CT, DJ-H and DJ-RSI will be assessed in the present study.

The use of tri-axial accelerometers, such as those integrated into MEMS devices, have demonstrated an ability to detect fatigue post exercise (Patterson *et al.*, 2011, Cormack *et al.*, 2013). Fatigue has been shown to result in an altered gait strategy during running

(Patterson *et al.*, 2011), which has been associated with reduced sprint and jump performance (Mendez-Villanueva *et al.*, 2008, Gathercole *et al.*, 2015), as well as increased injury risk (De Ste Croix *et al.*, 2015). Furthermore, it has been shown that during a fatigue-inducing RS protocol, large decrements in accelerometer load, specifically vertical acceleration were observed (Akenhead *et al.*, 2017). The result of an altered running strategy is determined by a reduction in the vertical acceleration of the centre of mass (Lee and Farley, 1998), which has previously been detected by an integrated accelerometer worn between the scapula (Barrett *et al.*, 2014). Cormack et al., (2013) attributed a reduction in vertical load, in fatigued elite AFL players, to reductions in force absorbing and generating capacity of the leg extensor muscles, which could potentially have implications for injury risk (De Ste Croix *et al.*, 2015, Barrett *et al.*, 2016). However, given the novelty of this area of research, no data currently exists on the sensitivity of tri-axial accelerometer load during a sub-maximal shuttle run, to training induced fatigue.

A multitude of different measures have been used within the literature to try and monitor fatigue on a daily and/or weekly basis, with varying degrees of sensitivity (see Chapter 2, Section 2.6). While a number of studies have assessed a fatigue response post match play (Nédélec *et al.*, 2012), or post training (Thorpe *et al.*, 2015) no one has examined the reproducibility of this response. For a fatigue monitoring measure to be successful, a three step approach was proposed. Firstly, a measure must show an acceptable level of test re-test reliability (Chapter 4), secondly it must be sensitive to changes in training load, i.e. changes greater than the MDC (documented in Chapter 4), are evident and finally, the response must be reproducible, i.e. a consistent response is seen, from the same training load, which is currently lacking within the literature.

5.1.2 Study aims

The aim of the present study was to firstly, establish the sensitivity of jump performance, tri-axial accelerometer variables and subjective wellness measures following a standardised training session and secondly, to establish the reproducibility of this training-induced fatigue response over two consecutive training weeks in elite youth football players.

5.2 Methods

5.2.1 Study design

This study was completed at the start of the in-season period (August) and consisted of eight testing sessions over a two week period. Players completed morning assessments of fatigue, prior to training. Each testing session consisted of morning ratings of subjective wellness, assessments of jump performance; CMJ, SJ and DJ, and a sub-maximal shuttle run test. Testing was completed before (-24 h, immediately pre) and after (+24h, +48 h) a strenuous standardised training session (see Chapter 3, Section 3.4.4). Training was controlled over the first two days, with a low training load session on day one and a very high training load session on day two, used as the fatigue inducing stimulus (Table 5.1). All testing sessions were conducted at the same time of day to minimise possible effects of circadian variation. These testing procedures were replicated over two consecutive weeks to enable the reproducibility of a fatigue response following the standardised training session to be established. All players were familiarised with the experimental procedures, which form part of their training and monitoring routinely.

Table 5.1. Descriptive statistics (mean ± SD) for training load of the strenuous standardised training session.

	Week 1	**Week 2**	**CV**	**ES (MBI)**
TD	7242 *(± 532)*	7221 *(± 514)*	5.5%	-0.04 (*Unclear*)
VHSR	597 *(± 85)*	591 *(± 71)*	8.7%	-0.07 (*Unclear*)
SPR	325 *(± 58)*	318 *(± 63)*	9.1%	-0.11 (*Unclear*)
AD Load	544 *(± 75)*	534 *(± 64)*	7.0%	-0.13 (*Unclear*)

Note: TD: total distance, VHSR: very high speed running, SPR: sprinting, AD Load: acceleration and deceleration load, CV: coefficient of variation, ES: effect size, MBI: magnitude based inference.

5.2.2 Participants

Twelve male youth football players (Age: 17.5 ± 0.5 years, Height: 177.0 ± 4.9 cm, Body Mass: 72.4 ± 8.9 kg), competing in the English Under-18 Premier League volunteered to participate in the present study. Participants were given full details of the study procedures and provided personal, and when under 18 years of age, parental/guardian written consent before participation. Institutional ethical approval was gained prior to any study involvement (HLSJF110915). Prior to inclusion in the study, all participants were deemed fit to participate and free of illness or injury by the club’s medical staff.

5.2.3 Procedures

5.2.3.1 Subjective wellness

A 5-item questionnaire to assess subjective ratings of fatigue, sleep quality, muscle soreness, stress and mood were collected as described in Chapter 3, Section 3.4.1.1. Reliability data is displayed in Chapter 4, Section 4.3.1 and Table 4.1.

5.2.3.2 Jump performance

Jump performance was assessed for a CMJ, SJ and DJ. Data were collected as described in Chapter 3, Section 3.4.1.2. Reliability data is displayed in Chapter 4, Section 4.3.2 and Table 4.2.

5.2.3.3 Sub-maximal shuttle run

A sub-maximal shuttle run was conducted as described in Chapter 3, Section 3.4.1.3. Reliability data is displayed in Chapter 4, Section 4.3.3 and Table 4.3.

5.2.3.4 Training load

Training load was monitored throughout the study in accordance with the description in Chapter 3, Section 3.4.3. Precision of the GPS signal throughout the study was; #sats: 11.9 ± 0.9; HDOP: 0.93 ± 0.13.

5.2.4 Statistical analysis

Visual inspection of histograms and Q–Q plots of raw data indicated no violation of normality assumptions. Raw data are therefore presented as the mean ± SD. To evaluate the sensitivity of each variable standardised changes in the mean (ES) were calculated between baseline (-24 h) and + 24 h, using a custom spreadsheet (Hopkins, 2017). The following criteria were adopted to interpret the magnitude of change; small, >0.2–0.6; moderate, >0.6–1.2; large, >1.2–2; and very large, >2.00 (Hopkins *et al.*, 2009). The magnitude of change was classified as a substantial increase or substantial decrease when there was a 75% or greater likelihood of the effect being equal to or greater than the ES ± 0.2 (small). Changes were classified as unclear when there was a 5% or greater likelihood of the effect being both positive and negative (Hopkins *et al.*, 2009).

To further assess if any substantial changes can be considered "real", based on the MDC (75% confidence level) calculated from Chapter 4, a signal-to-noise (S: N) ratio was calculated (Roe *et al.*, 2016). In order for a variable to be deemed capable of detecting a "real" change, and therefore sensitive to fatigue, the group mean change +24 h (signal) must be greater than the random within-subject variability (MDC - noise), as indicated by a ratio >1. This analysis was replicated for weeks one and two. For a variable to be categorised as having a reproducible fatigue response the S: N ratio had to be >1 for both weeks.

5.3 Results

Training load measures recorded during the strenuous standardised training session each week are displayed in Table 5.1. No substantial differences were observed between week one and two, indicating the standardised training session was the same during both weeks. Changes in the mean and ES with magnitude based inferences (MBI) from baseline to +24 h for the sub-maximal shuttle run test, jump performance and subjective wellness are provided in Tables 5.2, 5.3 and 5.4 respectively.

5.3.1 Sub-maximal shuttle run

No clear differences were found between baseline and immediately pre training during weeks 1 or 2. During the first week of testing, at +24 h, substantial differences were found for PL_{AP}, PL_{ML}, PL_V, $\%PL_{AP}$, $\%PL_{ML}$ and $\%PL_V$ (Table 5.2). At +48 h, substantial changes were shown for PL (ES 0.45 ± 0.42 CI, 84% likely positive), PL_{ML} (ES 0.58 ± 0.51 CI, 89% likely positive), $\%PL_{ML}$ (ES 0.37 ± 0.34 CI, 81% likely positive) and $\%PL_V$ (ES -0.52 ± 0.55 CI, 84% likely negative). All other measures displayed no clear differences from baseline at +48 h. During the second week of testing, a reproducible fatigue response at +24 h was shown for PL_{AP}, PL_{ML}, $\%PL_{AP}$, $\%PL_{ML}$ and $\%PL_V$ (Table 5.2). However, the only measures to display a S: N ratio greater than one across both weeks at +24 h were PL_{ML} and $\%PL_V$.

5.3.2 Jump performance

No clear differences were found between baseline and immediately pre training during weeks 1 or 2. During the first week of testing, at +24 h, substantial differences were found for DJ-H and DJ-RSI (Table 5.3). At +48 h, substantial increases in jump performance were shown for CMJ (ES 0.44 ± 0.20 CI, 97% very likely positive) and SJ (ES 0.33 ± 0.16 CI, 95% very likely positive). All other measures displayed no differences from baseline at 48 h post. During the second week of testing, a reproducible fatigue response at +24 h was shown for DJ-H and DJ-RSI (Table 5.3). However, the only jump performance measure to display a S: N ratio greater than one across both weeks at +24 h was DJ-RSI.

Table 5.2. Sensitivity 24 h post training for PlayerLoad™ (PL), individual component planes; anterior-posterior (PL_{AP}), mediolateral (PL_{ML}), and vertical (PL_{V}), and the percentage contribution of each plane.

		Baseline	24 h Post	Δ in Mean	ES	MBI	S:N Ratio
PL	Week 1	38.67 *(± 3.50)*	39.73 *(± 4.82)*	1.06 *(± 2.55)*	0.28 ± 0.68 *(Small)*	58% *Possible Increase*	0.77
	Week 2	38.47 *(± 4.02)*	40.66 *(± 3.88)*	2.19 *(± 1.94)*	0.51 ± 0.45 *(Small)*	88% * *Likely Increase*	1.59 **
PL_{AP}	Week 1	13.67 *(± 2.24)*	15.42 *(± 4.14)*	1.75 *(± 2.00)*	0.67 ± 0.77 *(Moderate)*	85% * *Likely Increase*	1.03 **
	Week 2	13.58 *(± 2.23)*	15.00 *(± 2.92)*	1.42 *(± 1.30)*	0.59 ± 0.54 *(Small)*	89% * *Likely Increase*	0.83
PL_{ML}	Week 1	13.33 *(± 1.87)*	14.42 *(± 2.11)*	1.08 *(± 1.05)*	0.54 ± 0.52 *(Small)*	87% * *Likely Increase*	1.02 **
	Week 2	13.50 *(± 1.38)*	14.75 *(± 1.36)*	1.25 *(± 0.97)*	0.84 ± 0.34 *(Moderate)*	100% * *Most Likely Increase*	1.18 **
PL_{V}	Week 1	28.33 *(± 2.50)*	27.08 *(± 2.81)*	-1.25 *(± 1.58)*	-0.47 ± 0.59 *(Small)*	78% * *Likely Decrease*	-0.96
	Week 2	28.08 *(± 2.35)*	27.25 *(± 3.19)*	-0.83 *(± 2.44)*	-0.33 ± 0.50 *(Small)*	67% *Possible Decrease*	-0.64
$\%PL_{AP}$	Week 1	24.6% *(± 2.6%)*	26.7% *(± 3.6%)*	2.1% *(± 1.5%)*	0.76 ± 0.53 *(Moderate)*	96% * *Very Likely Increase*	0.77
	Week 2	24.2% *(± 2.0%)*	26.2% *(± 3.5%)*	2.0% *(± 1.9%)*	0.95 ± 0.88 *(Moderate)*	92% * *Likely Increase*	0.73
$\%PL_{ML}$	Week 1	24.1% *(± 2.6%)*	25.4% *(± 2.4%)*	1.3% *(± 1.3%)*	0.46 ± 0.47 *(Small)*	83% * *Likely Increase*	0.66
	Week 2	25.5% *(± 2.0%)*	26.0% *(± 2.6%)*	0.5% *(± 1.1%)*	0.24 ± 0.49 *(Small)*	56% * *Possible Increase*	0.27
$\%PL_{V}$	Week 1	51.3% *(± 2.5%)*	47.9% *(± 3.7%)*	-3.4% *(± 1.7%)*	-1.27 ± 0.62 *(Large)*	100% * *Almost Certain Decrease*	-1.76 **
	Week 2	50.3% *(± 2.9%)*	47.8% *(± 4.3%)*	-2.6% *(± 2.6%)*	-0.82 ± 0.84 *(Moderate)*	89% * *Likely Decrease*	-1.31 **

Data presented as changes in mean ± SD; effect size (ES) ± 90% confidence intervals with magnitude based inference (MBI); signal: noise ratio.

* A substantial increase or decrease classified as ≥75% likelihood of the effect being greater than or equal to the ES ± 0.2 (small).

** Signal: Noise Ratio > 1.00 or < -1.00; variable has the ability to detect "real" change.

Table 5.3. Sensitivity 24 h post training for jump tests; countermovement jump height (CMJ), squat jump height (SJ), drop jump contact time (DJ-CT) drop jump height (DJ-H) and drop jump reactive strength index (DJ-RSI).

		Baseline	24 h Post	Δ in Mean	ES	MBI	S:N Ratio
CMJ	Week 1	35.18 *(± 4.92)*	35.28 *(± 4.56)*	0.10 *(± 1.01)*	0.02 ± 0.19 *(Trivial)*	91% *Likely Trivial*	0.04
	Week 2	36.18 *(± 3.85)*	35.74 *(± 4.06)*	-0.44 *(± 1.09)*	-0.11 ± 0.26 *(Trivial)*	Unclear	-0.18
SJ	Week 1	34.04 *(± 5.31)*	33.07 *(± 5.31)*	-0.97 *(± 0.86)*	-0.17 ± 0.15 *(Trivial)*	Unclear	-0.43
	Week 2	34.92 *(± 4.01)*	34.58 *(± 3.68)*	-0.34 *(± 1.19)*	-0.08 ± 0.28 *(Trivial)*	Unclear	-0.15
DJ-CT	Week 1	0.206 *(± 0.029)*	0.208 *(± 0.016)*	0.001 *(± 0.013)*	0.04 ± 0.42 *(Trivial)*	Unclear	0.09
	Week 2	0.203 *(± 0.030)*	0.206 *(± 0.029)*	0.003 *(± 0.004)*	0.10 ± 0.13 *(Trivial)*	92% *Likely Trivial*	0.21
DJ-H	Week 1	29.18 *(± 5.55)*	26.06 *(± 3.47)*	-2.74 *(± 1.50)*	-0.46 ± 0.25 *(Small)*	96% * *Very Likely Decrease*	-0.99
	Week 2	29.44 *(± 4.83)*	26.75 *(± 4.15)*	-2.69 *(± 1.43)*	-0.52 ± 0.28 *(Small)*	97% * *Very Likely Decrease*	-0.97
DJ-RSI	Week 1	1.45 *(± 0.35)*	1.29 *(± 0.24)*	-0.16 *(± 0.09)*	-0.43 ± 0.25 *(Small)*	94% * *Likely Decrease*	-1.00 **
	Week 2	1.50 *(± 0.38)*	1.34 *(± 0.34)*	-0.16 *(± 0.08)*	-0.40 ± 0.19 *(Small)*	96% * *Very Likely Decrease*	-1.01 **

Data presented as changes in mean ± SD; effect size (ES) ± 90% confidence intervals with magnitude based inference (MBI); signal: noise ratio.

* A substantial increase or decrease classified as ≥75% likelihood of the effect being greater than or equal to the ES ± 0.2 (small).

** Signal: Noise Ratio > 1.00 or < -1.00; variable has the ability to detect "real" change.

5.3.3 Subjective wellness

No clear differences were found in subjective wellness questionnaire responses between baseline and immediately pre training during weeks 1 or 2 (Table 5.4). During the first week of testing, at +24 h, substantial decreases were found for sleep quality, muscle soreness and total wellness (Table 5.4). During the second week of testing, a substantial decrease in subjective fatigue was evident (Table 5.4).However, no subjective measure displayed a S: N ratio of greater than one at any time point throughout the two-week study period.

Table 5.4. Sensitivity 24 h post training for subjective wellness measures.

		Baseline	24 h Post	Δ in Mean	ES	MBI	S:N Ratio
Fatigue	Week 1	3.00 *(± 0.85)*	2.83 *(± 0.72)*	-0.17 *(± 0.49)*	-0.18 ± 0.53 *(Trivial)*	Unclear	-0.36
	Week 2	3.25 *(± 0.62)*	3.00 *(± 0.60)*	-0.25 *(± 0.23)*	-0.37 ± 0.35 *(Small)*	80% * *Likely Decrease*	-0.53
Sleep Quality	Week 1	3.92 *(± 0.29)*	3.58 *(± 0.67)*	-0.33 *(± 0.40)*	-1.07 ± 1.30 *(Moderate)*	87% * *Likely Decrease*	-0.36
	Week 2	3.67 *(± 0.49)*	3.58 *(± 0.79)*	-0.08 *(± 0.47)*	-0.16 ± 0.88 *(Trivial)*	Unclear	-0.09
Muscle Soreness	Week 1	3.17 *(± 0.83)*	2.33 *(± 0.49)*	-0.83 *(± 0.37)*	-0.93 ± 0.41 *(Moderate)*	100% * *Most Likely Decrease*	-0.88
	Week 2	2.67 *(± 0.78)*	2.33 *(± 0.65)*	-0.33 *(± 0.51)*	-0.40 ± 0.61 *(Small)*	Unclear	-0.35
Stress	Week 1	3.33 *(± 0.78)*	3.17 *(± 0.83)*	-0.17 *(± 0.37)*	-0.20 ± 0.44 *(Small)*	Unclear	-0.18
	Week 2	3.33 *(± 0.78)*	3.50 *(± 0.80)*	0.17 *(± 0.58)*	0.20 ± 0.69 *(Small)*	Unclear	0.18
Mood	Week 1	3.83 *(± 0.58)*	3.75 *(± 0.62)*	-0.08 *(± 0.35)*	-0.13 ± 0.56 *(Trivial)*	Unclear	-0.09
	Week 2	3.67 *(± 0.78)*	3.75 *(± 0.75)*	0.08 *(± 0.60)*	-0.10 ± 0.72 *(Trivial)*	Unclear	0.09
Total Wellness	Week 1	17.25 *(± 2.18)*	15.67 *(± 1.97)*	-1.58 *(± 1.39)*	-0.68 ± 0.59 *(Moderate)*	91% * *Likely Decrease*	-0.62
	Week 2	16.58 *(± 1.83)*	16.17 *(± 2.29)*	-0.42 *(± 1.47)*	-0.21 ± 0.75 *(Small)*	Unclear	-0.16

Data presented as changes in mean ± SD; effect size (ES) ± 90% confidence intervals with magnitude based inference (MBI); signal: noise ratio.

- * A substantial increase or decrease classified as ≥75% likelihood of the effect being greater than or equal to the ES ± 0.2 (small).
- ** Signal: Noise Ratio > 1.00 or < -1.00; variable has the ability to detect “real” change.

5.4 Discussion

The aim of the current study was to assess the sensitivity of a subjective wellness questionnaire, measures of jump performance and sub-maximal shuttle run following a standardised training session; and subsequently establish the reproducibility of this fatigue response. The key findings from the present study were; 1) DJ-RSI, PL_{ML} and $\%PL_{V}$ were found to be sensitive measures of training-induced fatigue, displaying a reproducible response, that was greater than the MDC (calculated in Chapter 4), across both weeks; 2) CMJ, SJ and all subjective wellness measures were unable to detect a reproducible fatigue response, potentially calling into question their use in the monitoring of fatigue in athletes.

A novel aspect of the present study was the use of a sub-maximal shuttle run to assess tri-axial accelerometer data. A number of variables showed substantial changes at 24 h post training however only PL_{ML} and $\%PL_{V}$ were able to demonstrate a reproducible response, which was greater than the MDC established in Chapter 4, across both weeks of the study. When analysing accelerometer data, as a surrogate measure of movement strategy, it is important to consider the arbitrary nature of the data and resulting difficulty to discern underlying mechanisms. PL is the combination of the magnitude and frequency of the accelerations measured. Reductions in peak ground reaction forces during running have been reported previously when examining the effects of fatigue (Nikooyan and Zadpoor, 2012), as has increased step frequency (Padulo *et al.*, 2012, Girard *et al.*, 2016). Although ground reaction forces and step frequency are not available within the current data, it could be speculated that the decrease in vertical acceleration is a result of decreased ground reaction forces, and that this reduction supersedes the potential increase in step frequency. This would suggest a decrease in the force absorption and generating capacity of the musculoskeletal system (Latash and Zatsiorsky, 1993), which results in the reduction in $\%PL_V$, seen during sub-maximal shuttle running in the present study. The mechanisms behind these changes might be a decrease in lower extremity stiffness which has been associated with a decrease in physical performance and/or increased injury risk (Butler *et al.*, 2003). Future research should look to confirm a link between vertical acceleration ($\%PL_V$) and lower extremity stiffness.

In contrast with the negative changes in $\%PL_V$ there were substantial increases in PL_{ML} following the strenuous standardised training session. Research has shown that postural control and coordination during running deteriorate with fatigue (McClay and Cavanagh, 1994), possibly contributing to the increased mediolateral accelerations (PL_{ML}) found in the present study. This has important implications for practitioners as a fatigue induced reduction in postural control leading to an increased acceleration of the trunk, might increase the overall energy cost of running and increase injury risk (Barrett *et al.*, 2016).

The findings from the present study add to the growing body of evidence that tri-axial accelerometer data, specifically vertical and mediolateral movement, are associated with fatigue in team sport athletes (Cormack *et al.*, 2013, Akenhead *et al.*, 2017, Rowell *et al.*, 2018). The current study provides new knowledge to the current literature by establishing not only a fatigue response but also which measures can repeatedly detect a response from a standardised training stimulus. Practically, this sub-maximal assessment of fatigue is highly applicable to the team sport environment. This test uses data that is readily available to practitioners from the devices routinely worn in training. Furthermore, the sub-maximal nature of the test lends itself to being completed as part of the players' warm-up, meaning an assessment of fatigue can be gained with ease on a daily or weekly basis.

The only jump performance measure to show a reproducible response, which was greater than the MDC established in Chapter 4, was DJ-RSI. This is in line with previous research that has shown force-time variables such as the FT: CT ratio (Cormack *et al.*, 2008a) or RSI (Hamilton, 2009) to display a level of sensitivity to changes in training load. In the present study, DJ-CT did not show any changes under fatigue, it was reductions in DJ-H that resulted in the decrement in DJ-RSI. This might indicate that athletes are able to maintain contact time, however, they do not display the same force generating capacity when in a fatigued state, therefore jump height is reduced and consequently DJ-RSI. Studies have suggested that there is a link between lower extremity stiffness and performance during rebounding activities such as the DJ. Therefore, a decrease in lower extremity stiffness might have resulted in increased compliance of the lower body during the landing phase and subsequently decreases the ability to maximal utilise energy during the propulsive phase of a DJ (Farley *et al.*, 1991, Arampatzis *et al.*, 2001). The decrement in DJ-RSI evident in the present study is in agreement with previous findings which have shown substantial reductions in DJ-RSI 24 h post match play (Brownstein *et al.*, 2017).

An important, novel finding in the present study is the link between DJ-RSI and $\%PL_V$. Both reactive strength and vertical acceleration might be associated with lower extremity stiffness (Butler *et al.*, 2003, Lloyd *et al.*, 2009), it could therefore be suggested that similar mechanisms of fatigue are causing the apparent reductions in both assessments and further evidence that lower extremity stiffness is a key factor when assessing fatigue in athletes. Future research should look to investigate which training load variables are causing this apparent fatigue as this might help us further understand the underlying mechanisms and facilitate the management of fatigue via training load monitoring.

Other measures of jump performance assessed in the present study, CMJ and SJ, did not display any changes when in a fatigued state. This adds further evidence against the use of jump height as a measure of fatigue. It was shown by Gathercole et al. (2015), that CMJ height was not as sensitive as variables more indicative of CMJ strategy, such as eccentric and concentric duration. However, this analysis requires force-time data that involves expensive equipment that might not be readily available to some practitioners. The use of an optical measurement system might be more accessible, thus DJ-RSI could be used as a surrogate force-time measure, which has been shown in the present study to demonstrate a reproducible fatigue response.

Another key finding is the lack of reproducible response for subjective wellness. Measures of fatigue, sleep quality, muscle soreness and total wellness did show substantial changes in week 1 or 2 of testing however, the response to training was not replicated across both weeks for any subjective wellness measure. This is in contrast to recent research which has highlighted the superiority of subjective measures over objective measures (Saw *et al.*, 2015b). One potential reason for this is the design of the psychometric questionnaire used in the present study to assess subjective wellness. Using a 5-point Likert scale, with 1 point increments, gives a limited number of outcomes which can be selected. A change from a score of 5 to a score of 4 might subjectively not be that great to an athlete, however this is a 20% decrease. Changing the questionnaire to a larger scale (e.g. 1-10) might improve the reliability, making detectable changes more accessible and therefore improving the usefulness of subjective wellness measures for monitoring fatigue.

5.4.1 Conclusion

In summary, this study demonstrates firstly, the sensitivity of a number of measures to training induced fatigue following a standardised training session, and secondly, the reproducibility of this training-induced fatigue response in elite youth football players. Measurement of jump performance via DJ-RSI and tri-axial accelerometer variables %PLv and PL_{ML} gained via a sub-maximal shuttle run were found to show a fatigue response, greater than the MDC established in Chapter 4, over both weeks of testing. In contrast, no subjective wellness measures displayed a reproducible fatigue response. These data suggest that a simple assessment of DJ performance and a sub-maximal shuttle run can be used to accurately detect fatigue in a group of elite youth football players.

5.5 Perspective

The aim of Chapters 4 and 5 was to identify the most appropriate methods for monitoring fatigue, using a three step approach. In Chapter 4 the reliability of potenital fatigue measures was established, indicating that accelerometer data collected during a sub-maximal shuttle run and jump assessments; CMJ, SJ and DJ have good test re-test reliability. However, subjective wellness measures were deemed to have poor test re-test reliability.

Building on this, Chapter 5 looked to firstly establish the sensitivity of a training induced fatigue response and secondly, to determine if this response is reproducible. Chapters 4 and 5 have highlighted that DJ-RSI, PL_{ML} and $\%PL_{V}$ are three variables which are reliabile, sensitive to fatigue and have a reproducible fatigue response. These measures of fatigue were therefore used in Chapters 6 and 7 to assess the dose-response relationship between training load and fatigue (Chapter 6) and how improvements in aerobic training might facilitate a reduction in the fatigue response of football players (Chapter 7).

When assessing the sensitivity of the subjective wellness questionnaire to training induced fatigue, although substantial changes were apparent for subjective fatigue, muscle soreness and sleep quality during Chapter 5, no wellness measures displayed a response greater than the MDC at any time point. It has been discussed in Chapter 5 that this might be a result of the limited variation available with a 5-point Likert scale making the MDC large and detectible changes difficult to achieve. As part of Chapter 6, we therefore, re assessed the test re-test reliability of an adapted questionnaire, which increased the number of points on the Likert scale to 10 and reducing the number of items to only include; subjective fatigue, muscle soreness and sleep quality.

CHAPTER 6

6.0 DOSE-RESPONSE RELATIONSHIP BETWEEN TRAINING LOAD, FATIGUE AND FITNESS IN ELITE YOUTH FOOTBALL PLAYERS

Published papers from this chapter:

Fitzpatrick, J. F., Hicks, K. M. and Hayes, P. R. (2018) Dose-response relationship between training load and changes in aerobic fitness in professional youth soccer players. *International. Journal of Sports Physiology and Performance*, 13(10), 1365-1370.

Conference communications from this chapter:

Fitzpatrick, J. F., Hicks, K. M. and Hayes, P. R. (2017). Dose-response relationship between training load and changes in aerobic fitness in elite youth soccer players. *5th World Conference on Science in Soccer*, Rennes, France, 31st May – 2nd June 2017.

Fitzpatrick, J. F., McLaren, S., Hicks, K. M. and Hayes, P. R. (2018). Dose-response relationship between training load and changes in fatigue in elite youth soccer players. *BASES Student Conference*, Newcastle, UK, 12th – 13th April 2018.

6.1 Introduction

The concept of how training load affects performance is founded in the idea that training contributes to two specific outcomes, these are developed simultaneously by repeated bouts of training; fitness and fatigue (Banister *et al.*, 1975). The ability to understand these two factors and how they interact with training load is commonly termed the "dose-response relationship" and is considered a fundamental component of training (Akubat, 2014). The aim of a monitoring system is therefore to prescribe training with confidence that it will produce a predictable outcome within a defined period (Banister, 1991, Manzi *et al.*, 2009b). In order to achieve this aim practitioners must surmise the effect a given training dose has on both fitness and fatigue, which in turn will aid in their ability to structure a training program to maximise performance and reduce injury risk.

With regards to the interaction between training dose and fatigue a number of studies have established that football training and match play results in metabolic, neuromuscular and physical performance disturbances in the hours and days post (Bangsbo *et al.*, 2007, Nédélec *et al.*, 2012, Russell *et al.*, 2015, Brownstein *et al.*, 2017). In order to assess these disturbances a number of monitoring tools have been utilised including HR derived indices (Buchheit, 2014), biochemical markers (Morgans *et al.*, 2014), jump assessments (Malone *et al.*, 2015b) and subjective wellness questionnaires (Thorpe *et al.*, 2017). Despite the extensive literature on the post match fatigue response, the literature on monitoring fatigue during the training week, specifically the dose response relationship is lacking.

Chapters 4 and 5 of this thesis have highlighted that physical performance assessed via DJ-RSI, accelerometer variables; PL_{ML} and $\%PL_{V}$, have good test re-test reliability, are sensitive to training induced fatigue and that this fatigue response is reproducible. However, measures of subjective wellness were unable to detect a fatigue response, potentially due to poor test re-test reliability. As part of Chapter 6 we therefore re-designed the subjective wellness questionnaire, based on the findings from Chapters 4 and 5. This adapted questionnaire included only 3 items, subjective fatigue, muscle soreness and sleep quality. Furthermore, based on previous research (Impellizzeri and Maffiuletti, 2007) and our assumption that a greater range on the Likert scale might improve reliability the Likert scale for each item was changed from 1-5 to 1-10 (see Appendix C). The same methodology as described in Chapter 4 was used to assess test re-test reliability. Results indicate that subjective assessments of fatigue and muscle soreness demonstrate good reliability when on a 1-10 Likert scale. However, sleep quality demonstrated a low ICC (0.57) and the composite score for Total Wellness displayed poor internal consistency ($\alpha = 0.24$). The MDC for each subjective wellness measure is displayed in Table 6.1. It was therefore determined that subjective fatigue and muscle soreness would be used alongside DJ-RSI and accelerometer variables; PL_{ML} and $\%PL_V$ throughout Chapters 6 and 7 in order to assess a fatigue response.

Table 6.1. Reliability statistics for subjective wellness measures (1-10 Likert Scale – see Appendix C).

	Trial 1 (SD)	**Trial 2 (SD)**	**TE (90% CI)**	**ICC (90% CI)**	**CV (%) (90% CI)**	**MDC**	**MDC (%)**	**Required Sample Size**
Fatigue (au)	7.7 (1.3)	7.7 (1.1)	0.5 (0.4, 0.7)	0.83 (0.65, 0.92)	7.0 (5.5, 10.0)	0.8	10.6%	9
Sleep Quality (au)	7.9 (1.0)	7.6 (0.8)	0.6 (0.5, 0.8)	0.57 (0.25, 0.78)	7.9 (6.2, 11.2)	0.9	12.0%	9
Muscle Soreness (au)	7.4 (1.0)	7.1 (0.7)	0.4 (0.3, 0.6)	0.82 (0.63, 0.91)	5.5 (4.3, 7.7)	0.6	8.5%	9
Total Wellness (au)	23.0 (2.1)	22.4 (1.5)	0.8 (0.6, 1.1)	0.83 (0.65, 0.92)	3.5 (2.7, 4.8)	1.2	5%	9

Data are presented as group means (± SD) for each trial, typical error (TE), interclass correlation (ICC), coefficient of variation (CV), and minimum detectable change (MDC) (75% confidence level). The required sample size represented 80% power to detect the MDC.

Although these monitoring tools have shown acute changes following training (Chapter 5) it is important that they are sensitive to fluctuations in load (Meeusen *et al.*, 2013). The relationship between training load and fatigue monitoring tools has been previously established in other team sports, such as AFL (Buchheit *et al.*, 2013, Gastin *et al.*, 2013). Specifically in football, Thorpe et al. (2015) investigated the interaction between training load and next day fatigue in a number of monitoring tools in elite football players. Their findings suggest that subjective wellness, specifically subjective fatigue, to be the most sensitive marker, displaying *large* associations with fluctuations in daily training load. Other markers assessed such as CMJ and HR indices showed trivial to small associations, calling into question the usefulness of these markers when assessing players' fatigue status. This is in agreement with the results of this thesis (Chapter 5), which found CMJ height to not be sensitive to training induced fatigue, it could therefore be suggested that DJ-RSI might display a stronger dose-response relationship.

With regards to the interaction between training load and fitness there is limited evidence in team sports (Buchheit *et al.*, 2013, Taylor *et al.*, 2018) and in particular football (Akubat *et al.*, 2012, Manzi *et al.*, 2013). It was established within Chapter 2 that the internal response to a given external load is what drives aerobic fitness adaptation (Impellizzeri *et al.*, 2005) (Figure 2.3). A comparison of methods used to establish internal load in youth football players was investigated by Akubat et al. (2012). They found iTRIMP showed the strongest relationship with changes in fitness, as measured via speed at lactate threshold. In agreement, Manzi et al. (2013) found similar results with senior football players, showing *large* associations between iTRIMP and changes in $\dot{V}O_{2max}$ and in Yo-Yo IR1 performance. However, the assessment of iTRIMP can be time consuming, particularly in a team sport environment, limiting its ability to perform repeated assessments of a player's HR-blood lactate profile. With regards to external load GPS systems are widely used in elite team sports (Akenhead and Nassis, 2016) however, no research to date has investigated the dose-response relationship between external training load and changes in fitness in football players.

It has been proposed that when assessing the demands of training and match-play that an individualised approach to assessing external load might be advantageous (Abt and Lovell, 2009, Lovell and Abt, 2013, Hunter *et al.*, 2015). A number of methods have been employed to assess training load with reference to individual fitness characteristics gained via fields based assessments. Percentage of MSS has previously been used (Harley *et al.*, 2010), however, it has been highlighted that using one single fitness characteristic might not reflect the complete locomotor of a player (Weston, 2013, Hunter *et al.*, 2015). Alternatively, Mendez-Villanueva et al. (2013) used a technique which assessed field-based testing data to estimate a players' aerobic (MAS) and speed capabilities (MSS). This technique allows for an estimation of a players' ASR and has been used to establish the transition into sprint work (>30ASR) (Bundle *et al.*, 2003). Furthermore, Hunter et al. (2015) stated that this method of using field-based measures of MAS, MSS and ASR poses a more ecologically valid, economical and practical technique for individualising thresholds.

There is a lack of consensus within the literature about which methods are most appropriate for monitoring training load, specifically in regards to the dose-response relationship. The aforementioned dose-response studies have used a range of measures to quantity training and match load including sRPE (Buchheit *et al.*, 2013) and high speed running (>14.4 $km.h^{-1}$) (Thorpe *et al.*, 2015) and internal training load (iTRIMP) (Akubat *et al.*, 2012). Only one study to date has looked at the relationship between both arbitrary and individualised training load measures in football players (Scott and Lovell, 2017). This study found small to moderate relationships between training load and subjective fatigue and muscle soreness, however, no differences between arbitrary and individualised training load measures were apparent. A major criticism of this study is that, only subjective measures of fatigue were used, further, this study was conducted during a 21-day training camp where training load was not carefully controlled, which might have resulted in the low correlations observed. It has been shown in Chapter 5 that a standardised training session can be reliably used to induce a fatigue response, a more valid methodology might therefore be to manipulate the load within the standardised training session and assess the fatigue response of players following different magnitudes of training load.

6.1.1 Study aims

This Chapter was completed in two parts; Part I aimed to examine the dose-response relationship between different methods used to assess training load, specifically arbitrary and individualised speed thresholds, and markers of fatigue following three different standardised training sessions. Part II then aimed to examine the dose-response relationship between the same training load measures and markers of fitness over a 6-week in season training period.

6.2 Part I - Dose Response Relationship between Training Load and Fatigue

6.2.1 Methods

6.2.1.1 Study design

For this experimental research, a repeated measures randomised crossover design was employed. Data were collected over a 3-week period, during an in-season competition phase (September). Players' training loads were manipulated, during a standardised training session (see Section 3.4.4), on the same day each week (Tuesday) over a 3-week period, in a crossover design. The standardised training session was manipulated to elicit a “moderate”, “high” and “very high” training load. In order to assess a fatigue response morning ratings of subjective fatigue and muscle soreness, assessments of DJ-RSI performance and a sub-maximal shuttle run test were completed 24 h pre and 24 h post training each week. All testing sessions were conducted at the same time of day to minimise possible effects of circadian variation. All players were familiarised with the experimental procedures, which form part of their training and monitoring routinely.

6.2.1.2 Participants

Fourteen male youth football players (age: 17.0 ± 0.6 years, height: 178.7 ± 5.2, body mass: 71.0 ± 5.0), competing in the Under-18 Premier League agreed to participate in the present study. Participants were given full details of the study procedures and provided personal, and when under 18 years of age, parental/guardian, written consent before participation. Institutional ethical approval was gained prior to any study involvement (HLSJF100616). Prior to inclusion in the study, all participants were deemed fit to participate and free of illness or injury by the club’s medical staff.

6.2.1.3 Procedures

In order to assess training load via individualised speed thresholds, tests of MSS and MAS were conducted at start of the testing period.

Maximum sprint speed and maximal aerobic speed

A 40 m sprint test was used to assess MSS as described in Chapter 3, Section 3.4.2.1. A 1500 m time trial was conducted to assess MAS as described in Chapter 3, Section 3.4.2.2.

Reliability data for MSS and MAS is displayed in Chapter 6.1, Section 6.1.3.2 and Table 6.2.

Standardised training session

An overview of the standardised training session can be found in Chapter 3, Section 3.4.4. For the present study, all players completed the same "core" standardised training session on each of the three occasions. To elicit a "moderate" training load players only completed the "core" training. For the "high" and "very high" sessions additional running was conducted (15 s at 120% MAS, 15 s passive recovery), for the "high" session players completed one set of eight runs and for the "very high" session players complete 2 sets of eight runs. This type of additional running was in line with the high intensity interval training program conducted by Dupont et al. (2004). Players completed all three training sessions, over a 3-week period in a randomised crossover design. A comparison of the training loads elicited from the standardised training sessions can be seen in Figure 6.1.

Subjective wellness

Players' subjective ratings of fatigue and muscle soreness were collected as described in Chapter 3, Section 3.4.1.1. Reliability data is displayed in Table 6.1.

Jump performance

Jump performance was assessed via DJ-RSI. Data were collected as described in Chapter 3, Section 3.4.1.2. Reliability data is displayed in Chapter 4, Section 4.3.2 and Table 4.3.

Sub-maximal shuttle run

A sub-maximal shuttle run was conducted as described in Chapter 3, Section 3.4.1.3. Based on their test re-test reliability and sensitivity to fatigue PL_{ML} and $\%PL_V$ were the variables used in this study. Reliability data is displayed in Chapter 4, Section 4.3.3 and Table 4.4.

Training load

Training load was monitored throughout the study in accordance with the description in Chapter 3, Section 3.4.3. External training load variables collected were; TD, AD Load, metres and time covered above HSR (m>HSR, t>HSR), metres and time covered above very high speed running (VHSR) (m>VHSR, t>VHSR), metres and time covered above MAS (m>MAS, t>MAS) and metres and time covered above 30% ASR (m>30ASR, t>30ASR). Precision of the GPS signal throughout the study was; #sats = 12.9 ± 0.8; HDOP = 0.83 ± 0.14. To assess internal training load HRE and sRPE were also collected throughout the study as described in Chapter 3, Sections 3.4.3.2 and 3.4.3.3.

6.2.1.4 Statistical analysis

Visual inspection of histograms and Q–Q plots of raw data indicated no violation of normality assumptions. Raw data are therefore presented as the mean ± SD. Differences in training load across each of the three training sessions were compared via standardised changes in the mean (ES) using a custom spreadsheet (Hopkins, 2017). The following criteria were adopted to interpret the magnitude of change; >0.2–0.6, small; >0.6–1.2, moderate; >1.2–2, large; >2, very large (Hopkins *et al.*, 2009). The magnitude of change was classified as a substantial increase or substantial decrease when there was a 75% or greater likelihood of the effect being equal to or greater than the ES ± 0.2 (small). Changes were classified as unclear when there was a 5% or greater likelihood of the effect being both positive and negative (Hopkins *et al.*, 2009). Multicollinearity between training load measures was also assess via a Pearson's correlation coefficient matrix.

To understand the strength and direction of the dose-response relationship between training load and changes in fatigue measures, a univariate general linear model was used to calculate within subject correlation coefficients (r), with MBIs subsequently applied. The following criteria were adopted to interpret the magnitude of the relationship; 0.0-0.1 trivial; >0.1-0.3 small; >0.3-0.5 moderate; >0.5-0.7 large; >0.7-0.9 very large; >0.9-0.99 nearly perfect; 1.00 perfect (Hopkins *et al.*, 2009). Where the 90% confidence interval overlapped both the positive and negative threshold by ≥5% the relationship was deemed unclear (Hopkins *et al.*, 2009).

Linear mixed models were used to calculate the intercept and slope of each within subject relationship. Additionally, the minimum change in training load required to elicit the MDC in fatigue response was calculated by rearranging the regression equation:

$$\text{Training load to elicit MDC} = \text{MDC} - \text{Intercept} / \text{Slope}$$

6.2.2 Results

Mean group differences across the "moderate", "high" and "very high" training sessions were found to be substantial for every training load variable, indicating that the standardised training sessions were successful in manipulating training demands. Visual representation of training loads for TD, m>VHSR, t>MAS and sRPE is shown in Figure 6.1.

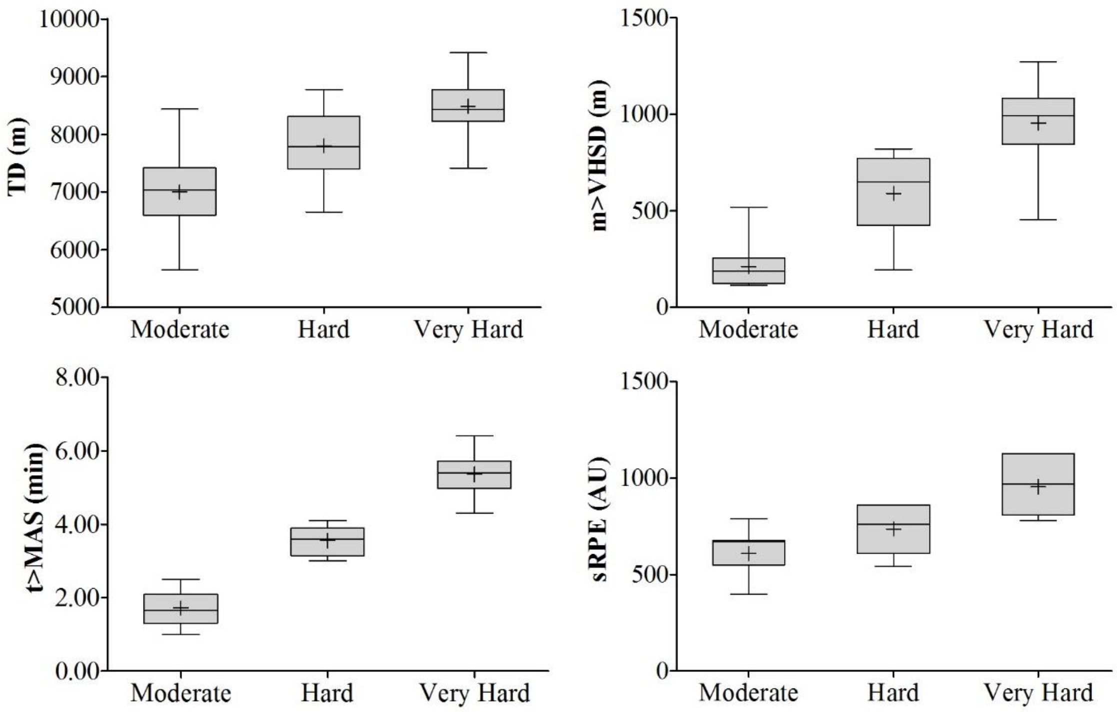

Figure 6.1. Box and whisker plots with median values, interquartile ranges and minimum and maximum values for TD, m>VHSR, t>MAS and sRPE across the three training sessions. + within each box plot represents the mean value.

Changes in subjective fatigue displayed *moderate* to *very large* relationships with all training load measures. Within subject correlations are displayed in Table 6.2. Linear mixed model variables such as intercept and slope are also shown in Table 6.2, along with the load required for each variable to elicit the MDC in subjective fatigue (10.6%). An example of the within subject relationship between t>MAS and % change in subjective fatigue is shown in Figure 6.2.

Table 6.2. Relationships between training load measures and percentage changes in subjective fatigue.

	TD (m)	**AD Load** (m)	**m>HSR** (m)	**t>HSR** (min)	**m>VHSR** (m)	**t>VHSR** (min)	**m>MAS** (m)	**t>MAS** (min)	**m>30ASR** (m)	**t>30ASR** (min)	**HRE** (AU)	**sRPE** (AU)
R	-0.65	-0.51	-0.69	-0.69	-0.71	-0.71	-0.70	-0.70	-0.74	-0.74	-0.34	-0.64
90% CI	-0.43, -0.80	-0.23, -0.71	-0.47, -0.82	-0.48, -0.83	-0.51, -0.84	-0.51, -0.84	-0.50, -0.83	-0.49, -0.83	-0.55, -0.86	-0.56, -0.86	-0.03, -0.60	-0.41, -0.80
MBI	*Likely Large*	*Possibly Large*	*Likely Large*	*Likely Large*	*Possibly Very Large*	*Possibly Very Large*	*Possibly Very Large*	*Possibly Very Large*	*Possibly Very Large*	*Possibly Very Large*	*Possibly Moderate*	*Likely Large*
Intercept (%)	56.1	36.2	-1.4	-1.0	-7.2	-7.4	-1.3	-1.2	-6.0	-6.3	-19.8	10.6
Slope (%)	-0.99	-13.88	-1.53	-5.32	-2.26	-8.60	-1.55	-5.39	-3.36	-12.75	-0.00	-0.04
TL to elicit MDC	6773	338	697	2.0	470	1.2	686	2.0	316	0.8	4916	523

Data displayed is the within subject correlation coefficients (r) with 90% confidence intervals (CI) and magnitude based inference (MBI). Linear mixed model intercept and slope data are presented along with the training load (TL) required to elicit the minimum detectible change (MDC) in subjective fatigue (10.6%).

Abbreviations: TD; total distance, AD Load; acceleration and deceleration distance >2m.s^{-2}, m>HSR; high speed running distance > 17 km.h^{-1}, t>HSR; high speed running time > 17 km.h^{-1}, m>VHSR; very high speed running distance > 21 km.h^{-1}, t>VHSR; very high speed running time > 21 km.h^{-1}, m>MAS; distance > MAS km.h^{-1}, t>MAS; time > MAS km.h^{-1}, m>30ASR; distance > 30% ASR km.h^{-1}, t>30ASR; time > 30% ASR km.h^{-1}, HRE; heart rate exertion, sRPE; session rating of perceived exertion.

Note: Slope (%) for distance variables is per 100m

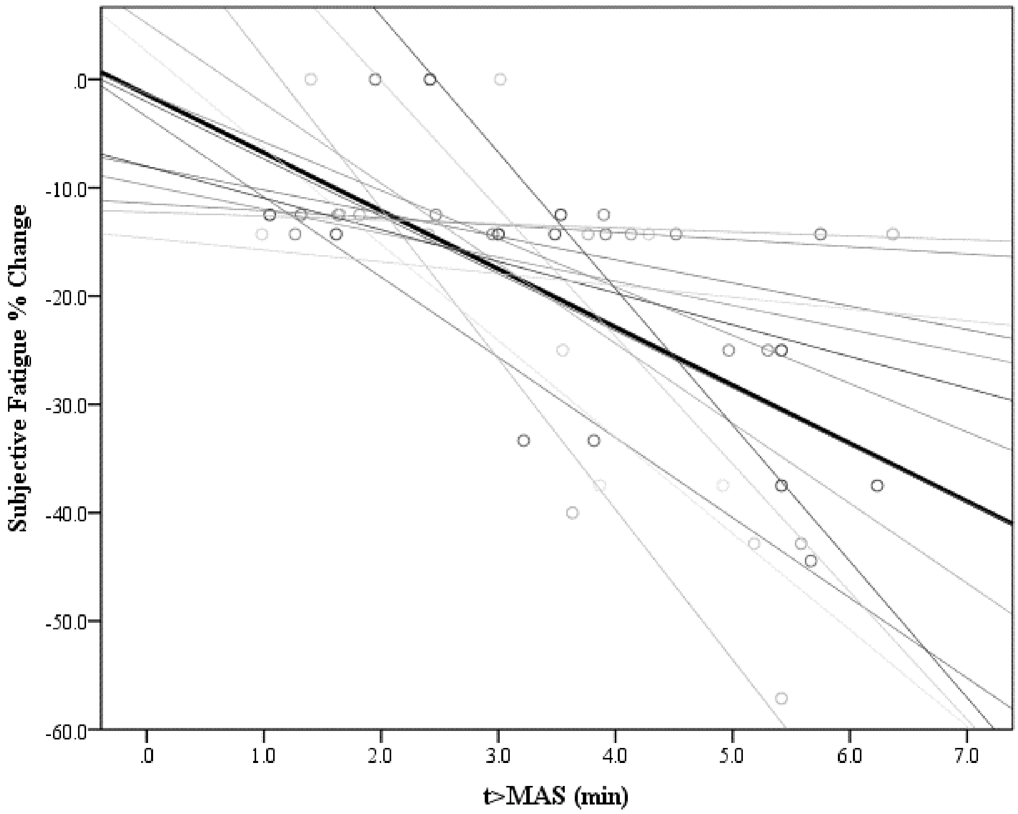

Figure 6.2. Within subjective correlation between t>MAS (min) and percentage change in subjective fatigue. Grey lines represent each individual's relationship and the black line represents the "mean" within subject relationship.

Changes in subjective soreness displayed *moderate* to *large* relationships with all training load measures. Within subject correlations are displayed in Table 6.3. Linear mixed model variables such as intercept and slope are also shown in Table 6.3, along with the load required for each variable to elicit the MDC in subjective soreness (8.5%).

Changes in DJ-RSI displayed *large* relationships with all training load measures. Within subject correlations are displayed in Table 6.4. Linear mixed model variables such as intercept and slope are also shown in Table 6.4, along with the load required for each variable to elicit the MDC in DJ-RSI (10.9%). An example of the within subject relationship between t>MAS and % change in DJ-RSI is shown in Figure 6.3.

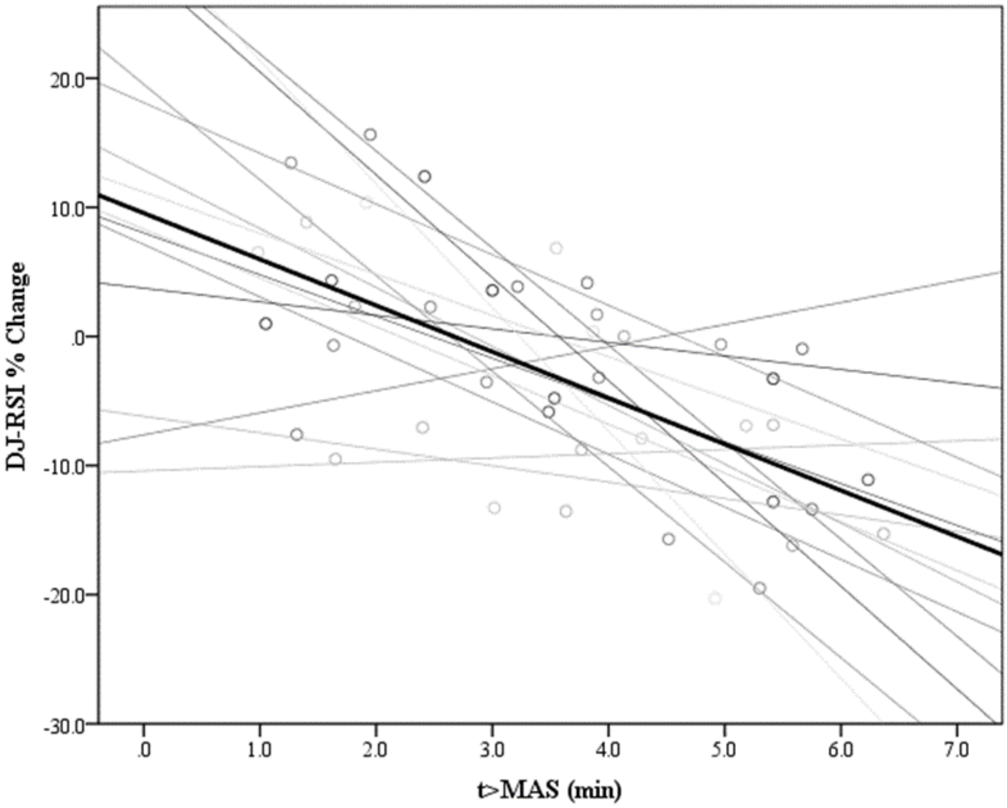

Figure 6.3. Within subjective correlation between t>MAS (min) and percentage change in DJ-RSI. Grey lines represent each individual's relationship and the black line represents the "mean" within subject relationship.

Changes in PL_{ML} displayed a *small* relationship with training load measures; m>HSR, t>HSR, m>MAS, t>MAS, m>30ASR and t>30ASR. All other training load measures showed an *unclear* relationship. Within subject correlations are displayed in Table 6.5. Linear mixed model variables such as intercept and slope are also shown in Table 6.5, along with the load required for each variable to elicit the MDC in PL_{ML} (7.5%).

Changes in $\%PL_V$ displayed *small* to *moderate* relationships with all training load measures. Within subject correlations are displayed in Table 6.6. Linear mixed model variables such as intercept and slope are also shown in Table 6.6, along with the load required for each variable to elicit the MDC in $\%PL_V$ (3.9%).

Table 6.3. Relationships between training load measures and percentage changes in subjective soreness.

	TD (m)	**AD Load** (m)	**m>HSR** (m)	**t>HSR** (min)	**m>VHSR** (m)	**t>VHSR** (min)	**m>MAS** (m)	**t>MAS** (min)	**m>30ASR** (m)	**t>30ASR** (min)	**HRE** (AU)	**sRPE** (AU)
R	-0.60	-0.37	-0.61	-0.62	-0.56	-0.56	-0.63	-0.63	-0.56	-0.56	-0.30	-0.61
90% CI	-0.36, -0.77	-0.06, -0.61	-0.36, -0.78	-0.38, -0.78	-0.29, -0.74	-0.29, -0.74	-0.39, -0.79	-0.39, -0.79	-0.29, -0.74	-0.3, -0.75	0.01, -0.57	-0.36, -0.78
MBI	*Likely Large*	*Possibly Moderate*	*Likely Large*	*Likely Large*	*Possibly Large*	*Possibly Large*	*Likely Large*	*Likely Large*	*Possibly Large*	*Possibly Large*	*Possibly Moderate*	*Likely Large*
Intercept (%)	62.8	12.2	0.4	0.2	-5.7	-5.9	-0.1	-1.2	-7.5	-8.0	30.8	10.9
Slope (%)	-1.07	-7.72	-1.61	-5.54	-2.45	-9.31	-1.62	-5.32	-2.88	-10.85	-0.21	-0.04
TL to elicit MDC	6696	268.0	552	1.6	348	0.9	527	1.6	296	0.8	191	478

Data displayed is the within subject correlation coefficients (r) with 90% confidence intervals (CI) and magnitude based inference (MBI). Linear mixed model intercept and slope data are presented along with the training load (TL) required to elicit the minimum detectible change (MDC) in subjective soreness (8.5%).

Abbreviations: TD; total distance, AD Load; acceleration and deceleration distance >2m.s^{-2}, m>HSR; high speed running distance > 17 km.h^{-1}, t>HSR; high speed running time > 17 km.h^{-1}, m>VHSR; very high speed running distance > 21 km.h^{-1}, t>VHSR; very high speed running time > 21 km.h^{-1}, m>MAS; distance > MAS km.h^{-1}, t>MAS; time > MAS km.h^{-1}, m>30ASR; distance > 30% ASR km.h^{-1}, t>30ASR; time > 30% ASR km.h^{-1}, HRE; heart rate exertion, sRPE; session rating of perceived exertion.

Note: Slope (%) for distance variables is per 100m

Table 6.4. Relationships between training load measures and percentage changes in drop jump reactive strength index (DJ-RSI).

	TD (m)	**AD Load** (m)	**m>HSR** (m)	**t>HSR** (min)	**m>VHSR** (m)	**t>VHSR** (min)	**m>MAS** (m)	**t>MAS** (min)	**m>30ASR** (m)	**t>30ASR** (min)	**HRE** (AU)	**sRPE** (AU)
R	-0.61	-0.58	-0.68	-0.67	-0.67	-0.68	-0.67	-0.67	-0.50	-0.50	-0.52	-0.66
90% CI	-0.36, -0.78	-0.33, -0.76	-0.46, -0.82	-0.45, -0.82	-0.45, -0.81	-0.46, -0.82	-0.44, -0.81	-0.44, -0.81	-0.22, -0.71	-0.22, -0.71	-0.24, -0.72	-0.43, -0.81
MBI	*Likely Large*	*Possibly Large*	*Likely Large*	*Likely Large*	*Likely Large*	*Likely Large*	*Likely Large*	*Likely Large*	*Possibly Large*	*Possibly Large*	*Possibly Large*	*Likely Large*
Intercept (%)	34.5	20.8	9.4	9.7	6.0	6.0	9.6	10.0	3.8	3.0	51.3	19.5
Slope (%)	-0.49	-5.59	-0.97	-3.45	-1.44	-5.58	-1.03	-3.72	-1.65	-5.48	-0.22	-0.03
TL to elicit MDC	9298	567.9	2104	6.0	1182	3.0	1994	5.6	895	2.5	285	1023

Data displayed is the within subject correlation coefficients (r) with 90% confidence intervals (CI) and magnitude based inference (MBI). Linear mixed model intercept and slope data are presented along with the training load (TL) required to elicit the minimum detectible change (MDC) in DJ-RSI (10.9%).

Abbreviations: TD; total distance, AD Load; acceleration and deceleration distance >2m.s^{-2}, m>HSR; high speed running distance > 17 km.h^{-1}, t>HSR; high speed running time > 17 km.h^{-1}, m>VHSR; very high speed running distance > 21 km.h^{-1}, t>VHSR; very high speed running time > 21 km.h^{-1}, m>MAS; distance > MAS km.h^{-1}, t>MAS; time > MAS km.h^{-1}, m>30ASR; distance > 30% ASR km.h^{-1}, t>30ASR; time > 30% ASR km.h^{-1}, HRE; heart rate exertion, sRPE; session rating of perceived exertion.

Note: Slope (%) for distance variables is per 100m

Table 6.5. Relationships between training load measures and percentage changes in PlayerLoad™ mediolateral (PL_{ML}).

	TD (m)	**AD Load** (m)	**m>HSR** (m)	**t>HSR** (min)	**m>VHSR** (m)	**t>VHSR** (min)	**m>MAS** (m)	**t>MAS** (min)	**m>30ASR** (m)	**t>30ASR** (min)	**HRE** (AU)	**sRPE** (AU)
R	-0.22	-0.13	-0.24	-0.24	-0.22	-0.22	-0.24	-0.25	-0.23	-0.24	0.23	-0.21
90% CI	0.10, -0.50	0.20, -0.43	0.08, -0.52	0.08, -0.52	0.11, -0.50	0.10, -0.50	0.08, -0.52	0.08, -0.52	0.09, -0.51	0.09, -0.52	-0.09, 0.51	0.12, -0.49
MBI	*Unclear*	*Unclear*	*Likely Small*	*Likely Small*	*Unclear*	*Unclear*	*Likely Small*	*Likely Small*	*Likely Small*	*Likely Small*	*Unclear*	*Unclear*
Intercept (%)			0.9	1.6			1.2	1.4	-1.0	-0.9		
Slope (%)			-0.30	-1.23			-0.34	-1.23	-0.40	-1.65		
TL to elicit MDC			2783	7.4			2566	7.2	1895	4.6		

Data displayed is the within subject correlation coefficients (r) with 90% confidence intervals (CI) and magnitude based inference (MBI). Linear mixed model intercept and slope data are presented along with the training load (TL) required to elicit the minimum detectible change (MDC) in PL_{ML} (7.5%).

Abbreviations: TD; total distance, AD Load; acceleration and deceleration distance >2m.s^{-2}, m>HSR; high speed running distance > 17 km.h^{-1}, t>HSR; high speed running time > 17 km.h^{-1}, m>VHSR; very high speed running distance > 21 km.h^{-1}, t>VHSR; very high speed running time > 21 km.h^{-1}, m>MAS; distance > MAS km.h^{-1}, t>MAS; time > MAS km.h^{-1}, m>30ASR; distance > 30% ASR km.h^{-1}, t>30ASR; time > 30% ASR km.h^{-1}, HRE; heart rate exertion, sRPE; session rating of perceived exertion.

Note: Slope (%) for distance variables is per 100m

Table 6.6. Relationships between training load measures and percentage changes in the percentage contribution of PlayerLoad™ vertical (%PL_V).

	TD (m)	**AD Load** (m)	**m>HSR** (m)	**t>HSR** (min)	**m>VHSR** (m)	**t>VHSR** (min)	**m>MAS** (m)	**t>MAS** (min)	**m>30ASR** (m)	**t>30ASR** (min)	**HRE** (AU)	**sRPE** (AU)
R	-0.41	-0.49	-0.43	-0.43	-0.45	-0.45	-0.44	-0.44	-0.27	-0.27	-0.38	-0.22
90% CI	-0.10, -0.64	-0.21, -0.70	-0.13, -0.66	-0.12, -0.65	-0.15, -0.67	-0.15, -0.67	-0.14, -0.66	-0.14, -0.66	0.05, -0.54	0.05, -0.54	-0.08, -0.63	-0.10, -0.51
MBI	*Possibly Moderate*	*Likely Moderate*	*Likely Moderate*	*Likely Moderate*	*Likely Moderate*	*Likely Moderate*	*Likely Moderate*	*Likely Moderate*	*Likely Small*	*Likely Small*	*Possibly Moderate*	*Possibly Small*
Intercept (%)	8.0	5.8	1.9	2.0	1.5	1.5	1.9	1.9	1.0	1.0	3.2	1.8
Slope (%)	-0.10	-1.42	-0.16	-0.57	-0.27	-1.01	-0.16	-0.55	-0.26	-0.96	-0.01	0.00
TL to elicit MDC	11484	683	3658	10.4	1479	3.9	3699	10.7	1549	4.1	513	2340

Data displayed is the within subject correlation coefficients (r) with 90% confidence intervals (CI) and magnitude based inference (MBI). Linear mixed model intercept and slope data are presented along with the training load (TL) required to elicit the minimum detectible change (MDC) in %PL_V (3.9%).

Abbreviations: TD; total distance, AD Load; acceleration and deceleration distance >2m.s^{-2}, m>HSR; high speed running distance > 17 km.h^{-1}, t>HSR; high speed running time > 17 km.h^{-1}, m>VHSR; very high speed running distance > 21 km.h^{-1}, t>VHSR; very high speed running time > 21 km.h^{-1}, m>MAS; distance > MAS km.h^{-1}, t>MAS; time > MAS km.h^{-1}, m>30ASR; distance > 30% ASR km.h^{-1}, t>30ASR; time > 30% ASR km.h^{-1}, HRE; heart rate exertion, sRPE; session rating of perceived exertion.

Note: Slope (%) for distance variables is per 100m

6.3 Part II – Dose Response Relationship between Training Load and Fitness

6.3.1 Methods

6.3.1.1 Study design

For this observational research, data were collected over a 6-week period, during an in-season competition phase (August-September). Throughout this period players took part in normal team training as prescribed by club coaching staff. This included 6 competitive matches, 23 training sessions, and 13 rest days. No structured conditioning was conducted throughout this study. Physical assessments of MAS and MSS were completed at the start and the end of the 6-week period, with training and match load monitored throughout.

6.3.1.2 Participants

Fourteen male youth football players (age: 17.1 ± 0.5 years, height: 178.3 ± 4.6 cm, body mass: 70.9 ± 5.8 kg) (defenders = 5, midfielders = 6, forwards = 3), competing in the English Under-18 Premier League agreed to participate in the study. Participants were given full details of the study procedures and provided personal, and when under 18, parental/guardian, written consent before participation. Institutional ethical approval was gained prior to any study involvement (HLSJF200117). Prior to inclusion in the study, all participants were deemed fit to participate and free of illness or injury by the football club's medical staff.

6.3.1.3 Procedures

In order to assess training load via individualised speed thresholds tests for MSS and MAS were conducted at the start of the testing period. These measures were also assessed at the end of the 6-week study period and used as physical performance measures.

Maximum sprint speed and maximal aerobic speed

A 40 m sprint test was used to assess MSS as described in Chapter 3, Section 3.4.2.1. A 1500 m time trial was conducted to assess MAS as described in Chapter 3, Section 3.4.2.2. Reliability data for MSS and MAS is displayed in Chapter 4, Section 4.3.4 and Table 4.4.

Training load

Training load was monitored throughout the study in accordance with the description in Chapter 3, Section 3.4.3. The same internal and external load variables were assessed as in Part I. Precision of the GPS signal throughout the study was #sats: 12.4 ± 0.5; HDOP: 0.81 ± 0.10.

6.3.1.4 Statistical analysis

Visual inspection of histograms and Q–Q plots of raw data indicated no violation of normality assumptions. Raw data are therefore presented as the mean ± SD. Pre-and post-measures of MAS and MSS were compared via standardised changes in the mean (ES) using a custom spreadsheet (Hopkins, 2017). The following criteria were adopted to interpret the magnitude of change; >0.2–0.6, small; >0.6–1.2, moderate; >1.2–2, large; >2, very large (Hopkins *et al.*, 2009)· The magnitude of change was classified as a substantial increase or substantial decrease when there was a 75% or greater likelihood of the effect being equal to or greater than the ES ± 0.2 (small). Changes were classified as unclear when there was a 5% or greater likelihood of the effect being both positive and negative (Hopkins *et al.*, 2009).

To understand the strength and direction of the dose-response relationship between the mean weekly training load and changes in fitness, Pearson's product moment correlation coefficients (r) were calculated. The following criteria were adopted to interpret the magnitude of the relationship; 0.0-0.1 trivial; >0.1-0.3 small; >0.3-0.5 moderate; >0.5-0.7 large; >0.7-0.9 very large; >0.9-0.99 nearly perfect; 1.00 perfect (Hopkins *et al.*, 2009). Where the 90% confidence interval overlapped both the positive and negative threshold by ≥5% the relationship was deemed unclear (Hopkins *et al.*, 2009).

Linear regression analysis was conducted following visual inspection of all relationships to identify a linear or curvilinear relationship. To determine the level of variance in the dependent variable explained by training load the coefficient of determination (R^2) was calculated, along with the intercept and slope of each relationship, via linear regression analysis. To understand the error associated with each does-response relationship the standard error of prediction (SEP) was calculated (Weir, 2005). Additionally, the minimum change in training load required to elicit the MDC in fitness was calculated for each relationship by rearranging the regression equation:

Training load to elicit MDC = MDC – Intercept / Slope

6.3.2 Results

A total of 387 training and match files were analysed for the 14 players during the 6-week in-season training period, the mean number of sessions per player was 29 (range: 24 – 29). A description of training loads over the 6-week period are shown in Table 6.7. Mean ± SD weekly and daily t>MAS during the training period are displayed in Figure 6.4.

The mean change in MAS over the training period was 0.11 ± 0.12 $km.h^{-1}$ from 17.04 to 17.15 $km.h^{-1}$ (ES = 0.15 ± 0.17, 69% possibly trivial) and the mean change for MSS was 0.27 ± 0.20 $km.h^{-1}$ from 31.71 to 31.98 $km.h^{-1}$ (ES = 0.16, 74% possibly trivial).

Table 6.7. Description of weekly training loads throughout the 6-week training period.

Training Load Measure	Weekly Mean ± SD
TD (m)	29,324 ± 4037
AD Load (m)	1477 ± 254
m>HSR (m)	2613 ± 576
t>HSR (min)	7.70 ± 1.66
m>MAS (m)	2512 ± 507
t>MAS (min)	7.41 ± 1.72
m>VHSR (m)	940 ± 242
t>VHSR (min)	2.35 ± 0.58
m>30ASR (m)	770 ± 176
t>30ASR (min)	1.95 ± 0.48
HRE (au)	957 ± 107
sRPE (au)	2091 ± 380

Note: TD: total distance, AD Load: acceleration and deceleration load, HSR: high speed running, MAS: maximal aerobic speed, VHSR: very high speed running, ASR: anaerobic speed reserve, HRE: heart rate exertion, sRPE: session rating of perceived exertion.

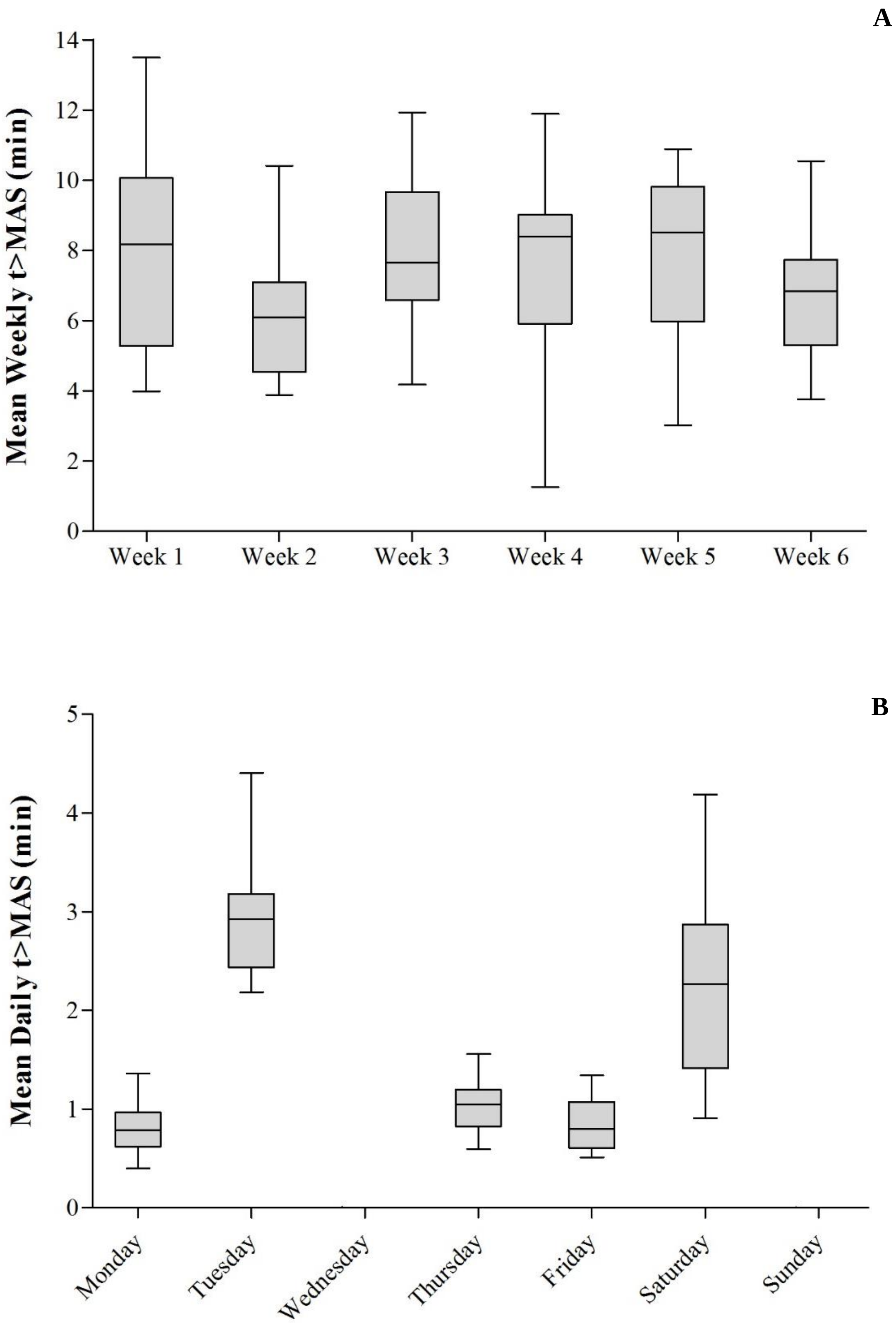

Figure 6.4. Box and whisker plots with median values, interquartile ranges and minimum and maximum values for weekly (A) and daily (B) time spent above maximal aerobic speed (t>MAS) during the 6-week in-season training period.

A *very large* linear relationship was found between t>MAS and changes in MAS (r = 0.77 [90% CI 0.48 to 0.91], R^2 = 0.59) (Figure 6.5). Also, *large* relationships were found between t>30ASR (r = 0.62 [90% CI 0.22 to 0.84], R^2 = 0.38), m>MAS (r = 0.50 [90% CI 0.06 to 0.78], R^2 = 0.25) and changes in MAS. Relationships between all other mean weekly arbitrary and individualised training load measures and changes in fitness parameters were found to be *unclear* (Tables 6.8 and 6.9).

Other external load measures, TD (r = 0.26 [90% CI -0.23 to 0.64]) and AD Load (r = 0.20 [90% CI -0.29 to 0.60]) displayed *unclear* relationships with changes in MAS. Similarly, internal load measures, HRE (r = -0.21 [90% CI -0.61 to 0.28]) and sRPE (r = 0.22 [90% CI -0.26 to 0.62]) were also *unclear*. In contrast, relationships with changes in MSS were identified for TD (r = 0.46 [90% CI 0.00 to 0.76] *possibly* moderate, R^2 = 0.21), AD Load (r = 0.57 [90% CI 0.15 to 0.81] *possibly* large, R^2 = 0.32) and HRE (r = 0.40 [90% CI -0.07 to 0.73] *possibly* moderate, R^2 = 0.16). However, sRPE (r = 0.37 [90% CI -0.11 to 0.71]) displayed an *unclear* relationship with changes in MSS.

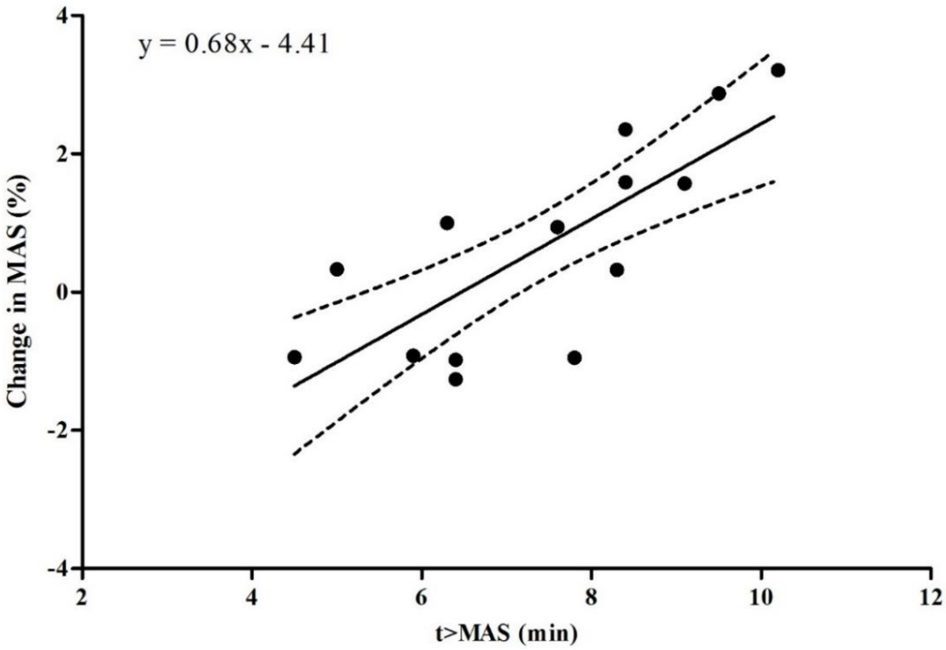

Figure 6.5. Linear relationship between mean weekly time spent above maximal aerobic speed (t > MAS) and percentage change in MAS during the 6-week in-season training period. Intercept = −4.41%, slope = 0.68%, and SEP = 1.02%.

Table 6.8. Relationships between mean weekly training load measures and percentage changes in maximal aerobic speed (MAS).

	TD (m)	**AD Load** (m)	**m>HSR** (m)	**t>HSR** (min)	**m>VHSR** (m)	**t>VHSR** (min)	**m>MAS** (m)	**t>MAS** (min)	**m>30ASR** (m)	**t>30ASR** (min)	**HRE** (AU)	**sRPE** (AU)
R	0.26	0.20	0.22	0.37	-0.07	0.05	0.50 *	0.77 *	0.20	0.62 *	-0.21	0.22
90% CI	-0.23, 0.64	-0.29, 0.60	-0.27, 0.62	-0.10, 0.71	-0.51, 0.40	-0.42, 0.50	0.06, 0.78	0.48, 0.91	-0.28, 0.61	0.22, 0.84	-0.61, 0.28	-0.26, 0.62
MBI	*Unclear*	*Unclear*	*Unclear*	*Unclear*	*Unclear*	*Unclear*	*Possibly Large*	*Possibly Very Large*	*Unclear*	*Possibly Large*	*Unclear*	*Unclear*
Intercept (%)							-3.17	-4.41		-3.16		
Slope (%)							1.52	0.68		1.96		
SEP (%)							1.37	1.02		1.25		
TL to elicit MDC							3057	8.6		2.4		

Data are presented as Pearson’s correlation coefficients (r) with 90% confidence intervals (CI) and magnitude based inference (MBI). Linear regression intercept, slope and standard error of prediction (SEP). Also displayed is the minimum training load (TL) required to elicit the MDC in MAS (1.5%).

Abbreviations: TD; total distance, AD Load; acceleration and deceleration distance >2m.s^{-2}, m>HSR; high speed running distance > 17 km.h^{-1}, t>HSR; high speed running time > 17 km.h^{-1}, m>VHSR; very high speed running distance > 21 km.h^{-1}, t>VHSR; very high speed running time > 21 km.h^{-1}, m>MAS; distance > MAS km.h^{-1}, t>MAS; time > MAS km.h^{-1}, m>30ASR; distance > 30% ASR km.h^{-1}, t>30ASR; time > 30% ASR km.h^{-1}, HRE; heart rate exertion, sRPE; session rating of perceived exertion.

Note: Slope (%) for distance variables is per 1000m

Table 6.9. Relationships between mean weekly training load measures and percentage changes in maximum sprint speed (MSS).

	TD (m)	**AD Load** (m)	**m>HSR** (m)	**t>HSR** (min)	**m>VHSR** (m)	**t>VHSR** (min)	**m>MAS** (m)	**t>MAS** (min)	**m>30ASR** (m)	**t>30ASR** (min)	**HRE** (AU)	**sRPE** (AU)
R	0.46 *	0.57 *	0.32	0.34	0.25	0.27	0.30	0.21	-0.09	-0.15	0.40 *	0.37
90% CI	0.00, 0.76	0.15, 0.81	-0.17, 0.68	-0.15, 0.69	-0.24, 0.64	-0.22, 0.65	-0.18, 0.67	-0.28, 0.61	-0.53, 0.39	-0.57, 0.33	-0.07, 0.73	-0.11, 0.71
MBI	*Possibly Moderate*	*Possibly Large*	*Unclear*	*Unclear*	*Unclear*	*Unclear*	*Unclear*	*Unclear*	*Unclear*	*Unclear*	*Possibly Moderate*	*Unclear*
Intercept (%)	-3.68	-3.64									-4.07	
Slope (%)	0.15	3.01									0.01	
SEP (%)	1.25	1.16									1.28	
TL to elicit MDC	37283	1882									1195	

Data are presented as Pearson's product moment correlation coefficients (r) with 90% confidence intervals (CI) and magnitude based inference (MBI). Linear regression intercept, slope and standard error of prediction (SEP). Also displayed is the minimum training load (TL) required to elicit the MDC in MSS (2.0%).

Abbreviations: TD; total distance, AD Load; acceleration and deceleration distance >2m.s^{-2}, m>HSR; high speed running distance > 17 km.h^{-1}, t>HSR; high speed running time > 17 km.h^{-1}, m>VHSR; very high speed running distance > 21 km.h^{-1}, t>VHSR; very high speed running time > 21 km.h^{-1}, m>MAS; distance > MAS km.h^{-1}, t>MAS; time > MAS km.h^{-1}, m>30ASR; distance > 30% ASR km.h^{-1}, t>30ASR; time > 30% ASR km.h^{-1}, HRE; heart rate exertion, sRPE; session rating of perceived exertion.

Note: Slope (%) for distance variables is per 1000m

6.4 Discussion

The aim of this chapter was to examine the dose-response relationship between various training load measures, markers of fatigue and assessments of fitness in elite youth football players. Part I looked at the relationship between training load and fatigue. The key findings suggest there is a *large* to *very large* dose-response relationship between training load and DJ-RSI, subjective fatigue and muscle soreness. Furthermore, some *small* to *moderate* relationships were evident between training load and accelerometer measures; PL_{ML} $\%PL_{V}$. Part II looked at the relationship between training load and fitness. Finding that training load measures utilising individualised speed thresholds, specifically t>MAS, demonstrated a *very large* relationship with changes in aerobic fitness. When the key findings from both studies are evaluated concurrently, t>MAS appears to be an important training load measure that can demonstrate a strong dose-response relationship with both fatigue and fitness.

This is the first investigation to assess the relationships between various measures of training load and changes in fitness and fatigue. It has previously been shown that using individualised thresholds could better represent the true physiological demands of football training and match play (Abt and Lovell, 2009, Hunter *et al.*, 2015). However, linking these individualised measures to specific training outcomes, such as improvements in aerobic fitness and training induced fatigue have not previously been researched. The two studies in this chapter found that using an individualised method on monitoring training, based on the time spent above an individual's MAS, has the strongest relationship with both changes in aerobic fitness and training induced fatigue. Evidenced via decrements in DJ-RSI performance, altered movement strategy during a sub-maximal shuttle run and perceptions of fatigue and muscle soreness. This adds important information to the current body of evidence on evaluating training loads, allowing practitioners to clearly understand various physical outcomes from a given training load.

It has been shown that HSR (>19.8 km.h^{-1}) is one of the most commonly used measures of training load in elite football (Akenhead and Nassis, 2016). This chapter has demonstrated that although arbitrary thresholds of 17.0 km.h^{-1} (HSR) and 21.0 km.h^{-1} (VHSR) presented some *large* to *very large* correlations with measures of fatigue (Tables 6.2-6.4), *unclear* correlations were found with changes in fitness parameters (Tables 6.7-6.8). This challenges the usefulness of arbitrary measures for assessing training load. Additionally, as the dose-response relationship between HSR, VHSR and measures of fitness is *unclear*, it is very difficult for practitioners to make informed decisions about the desired training outcomes based on arbitrary speed thresholds, which could lead to over/under-training, injury or illness.

Part I has built upon the limited research examining the dose-response relationship between training load and fatigue in football players (Thorpe *et al.*, 2015, Scott and Lovell, 2017). Both of these studies found a relationship with subjective markers of fatigue, however, the relationship found in the present study is substantially stronger. This might be down to methodological differences, as both studies assessed fatigue on a daily basis within a short training period (17-21 days), with no control over the players training and match schedule or other confounding variables such as gym training, diet or lifestyle. Whereas, the present investigation, utilised a robust randomised crossover design, within which players took part in three standardised training sessions that successfully managed to elicit varying degrees of training load (Figure 6.1). The reproducibility of this standardised training session, and the subsequent fatigue response had already been established in Chapter 5. In this study, varying the volume and intensity of the standardised session in a crossover design might have eradicated some of the confounding variables seen in previous literature (Thorpe *et al.*, 2015, Scott and Lovell, 2017), resulting in a stronger, and more consistent dose-response relationship.

In Part I the fatigue experienced after training increased with an increase in training load. The following tests were able to detect this; DJ-RSI, subjective fatigue and muscle soreness, as seen by the *large* to *very large* dose-response relationships. However, along with the strength of the relationship it is also important to assess the model parameters, such as, the intercept, slope and the training load required to elicit the MDC in each fatigue measure. This analysis provided a deeper insight into the data; for example, when assessing the intercept of each relationship with t>MAS it can be seen that for DJ-RSI this is +10.0%. This suggests that players need to have completed a certain amount of training (2.7 minutes) before any negative responses in DJ-RSI are evident, and around 5.6 minutes is needed to be confident that a 'real' decrement in DJ-RSI performance has taken place (MDC = -10.9%). In contrast, subjective measures of fatigue and muscle soreness start to experience decrements when training load increases above zero (intercept = -1.2%), with only 2.0 minutes t>MAS needed to elicit the MDC of -10.6% in subjective fatigue. This could be an indication of the subjective nature of these measures, as training load accumulates players perceive they have experienced some level of fatigue or muscle soreness. However, a greater amount of training load is required to experience 'real' decrements in objective measures. These results highlight the differences between objective and subjective markers of fatigue and that different underlying mechanisms might be the cause of fatigue. This is in agreement with previous literature (Thorpe *et al.*, 2015). The study by Thorpe *et al.* (2015) found a *large* relationship between arbitrary HSR and subjective fatigue. However, *trivial* to *small* relationships were found with objective fatigue markers; CMJ height and HRV. A possible reason for this discrepancy could be that training load was not substantial enough to induce a fatigue response in the objective markers, which has been suggested in previous research (Thorpe *et al.*, 2016).

The findings from the present chapter would corroborate this suggestion, as substantially more training load was required to induce a fatigue response in objective compared to subjective measures. Further research is needed to understand the level of change in these markers that is anchored to substantial changes in sports specific performance and/or injury risk. This will add to a practitioners understanding of what a detectable change is and what changes in fatigue measures are practically important.

A novel aspect of the present study was the inclusion of time spent above both arbitrary and individualised speed thresholds. When analysing external training loads the most commonly used measure is distance covered above a specific threshold, this is evident in both research and practice (Malone *et al.*, 2015a, Akenhead *et al.*, 2016, Akenhead and Nassis, 2016, Jones *et al.*, 2017). Findings from this chapter suggest that time spent above an individualised speed threshold might be a more robust measure of training load, given the stronger associations between time variables compared to distance variables in Part II of this chapter. This would be in line with research on endurance athletes where time spent at or near $\dot{V}O_{2max}$ is an important consideration when looking to improve aerobic fitness (Billat *et al.*, 1999). However, two review articles by Midgley et al. (2006, 2007) have suggested that although previous research (Mikesell and Dudley, 1984, Billat *et al.*, 1999, Smith *et al.*, 1999, Billat *et al.*, 2002) supports the premise that high-intensity training might be effective for enhancing $\dot{V}O_{2max}$, the efficacy of specific training interventions needs to be established. They also state well controlled studies in which interventions are compared with protocols involving different training intensities are required. The differences between time spent and distance covered above MAS, observed in the present study, might be a consequence of players running at higher speeds. This will lead to a large number of metres covered in a small amount of time. Therefore if t>MAS is the parameter practitioners are looking to target, running at the speed associated with MAS, could be a key factor when looking to improve aerobic fitness in football players.

This two part study is the first to assess the dose-response relationship between training load and both fitness and fatigue simultaneously. Part I showed that all training load variables had strong relationships with DJ-RSI, %PL_V and subjective wellness measures. This might be to do with the high multicollinearity between training load variables (see Appendix E). The high multicollinearity observed is possibly due to training being assessed acutely over only three training sessions that were standardised to elicit certain loads. Therefore, only very small between measure differences were seen in the training load-fatigue relationship. However, when training was analysed longitudinally in Part II, clear between measure differences were apparent. This indicates that differences between arbitrary and individualised measures are not as substantial on a session to session basis. However, when training is accumulated over a number of days and weeks these small differences become magnified, and the dose-response relationship with fitness was stronger for individualised measures. Therefore, as understanding the relationship with both fitness and fatigue is the goal of a successful monitoring system, an individualised approach, specifically the calculation of t>MAS should be of high importance to practitioners.

This chapter has demonstrated that t>MAS has a strong relationship with both fitness and fatigue measures. Although an accumulation of t>MAS on a weekly basis will improve aerobic fitness, too much during a single training session will result in a large amount of fatigue. This highlights the importance of careful planning of an athletes daily and weekly training schedule. Given the mean weekly t>MAS of 7.4 minutes seen in Part II and the trivial mean change in fitness, a greater t>MAS might be needed throughout the training week if players are to improve their fitness. By using the linear regression model parameters displayed in Table 6.8 an estimated percentage change in aerobic fitness can be obtained from a given mean weekly t>MAS. For example, 6.5 minutes per week over a 6-week period would estimate a 0% change in fitness, which might be the target of an in-season maintenance phase. However, it is important to appreciate the standard error of prediction within each model, for t>MAS this is 1% (Table 6.8). This means 6.5 minutes per week might result in a -1% to +1% change in aerobic fitness. If the desired outcome is to improve fitness, a target that is greater than the MDC will be more appropriate. Findings suggests 8.6 minutes per week would estimate an improvement of 1.5% ± 1.0%, giving a range of 0.3% to 2.3% change in aerobic fitness. Contrary to this, 8.6 minutes will result in a substantial amount of fatigue if not programmed in manageable doses throughout the week. Given that players on average spend 2.3 minutes above MAS during match play (Figure 6.4B) this leaves 6.3 minutes to be accumulated each week during training. A recommendation might be to not complete more than 5 minutes t>MAS on a given day unless it is followed by a 'rest' day, as around 5 minutes t>MAS is estimated to result in a substantial decrement in DJ-RSI performance. In summary, this chapter has demonstrated that t>MAS has a strong relationship with both changes in aerobic fitness and changes in fatigue. It is therefore recommended that t>MAS is a key measure for practitioners when monitoring players' training and match load. However, careful programming of this variable is required to improve fitness without accumulating excessive levels of fatigue on a daily basis. The dose-response models documented within this chapter can be used by practitioners to estimate both the fitness and fatigue response from a given training load.

6.4.1 Conclusion

This is the first series of investigations to examine the dose-response relationship between a range of measures quantifying training load and changes in fitness and fatigue. Results indicate individualising training load, specifically the measurement of time above MAS has a *very large* relationship with both subjective fatigue and aerobic fitness. Other measures such as TD covered and arbitrary HSR did show strong relationships with certain fatigue measures, however, *unclear* relationships with aerobic fitness. The practical applications discussed might help practitioners to effectively plan their training programs based on the desired training outcome. Detailed recommendations have been given, showing how linear regression and linear mixed model analysis can be used to estimate both the fitness and fatigue response from a given training load and how these relationships will need to be managed to improve fitness while minimising the accumulation of fatigue.

6.5 Perspective

In Chapters 4 and 5 the reliability and sensitivity of markers of fatigue was established. This highlighted DJ-RSI performance, accelerometer variables; PL_{ML} and $\%PL_{V}$ and subjective ratings of fatigue and muscle soreness, were reliable, sensitive and able to detect a reproducible fatigue response following a standardised training session. Chapter 6 looked to build upon this and in Part I assessed the dose-response relationship between these fatigue measures and a range of training load measures. Of special interest was the difference between using arbitrary or individualised speed thresholds based on a players MAS and MSS. Part II of this chapter examined the dose-response relationship between the same measures of training load and measures of fitness. Concurrently, the results from these two studies indicate that t>MAS is a key training load variable as it has a very strong relationship with both measures of aerobic fitness and measures of fatigue. Furthermore, these two studies have built upon the knowledge gained in Chapter 5 to show DJ-RSI, $\%PL_V$ and subjective measures of fatigue and muscle soreness demonstrate a clear response based on a players training load. New knowledge was further provided in Part II, indicating t>MAS is strongly related to improvements in aerobic fitness. This was the first piece of research to investigate the relationship between individualised speed thresholds and measures of fitness in football players.

So far this thesis has established the dose-response relationship between training load, fitness and fatigue. As a logical extension of this, Chapter 7 will look to validate these findings by investigating the relationship between changes in aerobic fitness and the fatigue response following a standardised training session. For practitioner's improvements in fitness is often their primary goal. The information gained in Chapter 6 – Part II will be used to develop a novel MAS intervention that looks to improve aerobic fitness by prescribing supplementary running that will increase weekly t>MAS. Secondly, a standardised training session, similar to that used in Chapters 5 and 6, will be completed pre and post intervention to assess a players training induced fatigue response. Based on previous literature and the findings from this thesis it can be hypothesised that improvements in aerobic fitness will be evident from the MAS intervention and this improvement in aerobic fitness will attenuate the fatigue experienced post standardised training session, which will have far reaching implications for practitioners working in football.

CHAPTER 7

7.0 RELATIONSHIP BETWEEN CHANGES IN AEROBIC FITNESS AND A TRAINING INDUCED FATIGUE RESPONSE IN ELITE YOUTH FOOTBALL PLAYERS

Conference communications from this chapter:

Fitzpatrick, J. F., Musham, C., Hicks, K. M. and Hayes, P. (2019). Relationship between changes in aerobic fitness and a training induced fatigue response in elite youth football players. *24th annual Congress of the European College of Sport Science*, Prague, Czech Republic, 3rd – 6th July 2019.

7.1 Introduction

In recent years the physical demands of elite level football have significantly increased, with high speed running and sprinting increasing by up to 35% (Barnes *et al.*, 2014). In addition, the number of matches played throughout a season has also increased, with players participating in up to 50 games over the course of a competitive season, some of which might occur with limited recovery time (<72 h) (Carling *et al.*, 2015). With the demands of training and matches increasing and available recovery times decreasing (Nédélec *et al.*, 2012, Morgans *et al.*, 2014), methods for reducing fatigue and/or improving subsequent recovery are of paramount importance to elite football players.

The previous chapters in this thesis have established the relationship between training load, fitness and fatigue. The findings indicate that the accumulated weekly time spent above MAS is an important consideration when looking to improve aerobic fitness and that this measure (t>MAS) can be used to accurately estimate the fitness response from a given training load. Based on previous research it could be suggested that improvements in aerobic fitness will enhance the ability to recover between repeated bouts of high intensity exercise (Tomlin and Wenger, 2001). An increase in aerobic fitness could therefore reduce the fatigue associated with football training and match play.

The attenuation of fatigue from an improvement in aerobic fitness likely comes from a number of possible mechanisms, resulting in a reduced level of fatigue for a given training load. Repeated bouts of high intensity activity within football results in decreased ATP-PCr stores (Krustrup *et al.*, 2006). If the high intensity bout exceeds more than a few seconds anaerobic glycolysis will be required to provide energy (Gaitanos *et al.*, 1993). The metabolic consequences of increased anaerobic glycolysis are an increase in H^+ concentration and decreased pH. This will adversely affect performance by disrupting contractile processes (Sahlin, 1992), which results in an inability to maintain power output. The physiological adaptations that occur from aerobic training, such as, increased concentrations of aerobic enzymes, increased mitochondrial density (Holloszy and Coyle, 1984) and increased myoglobin (Saltin and Rowell, 1980), all contribute to improved oxygen diffusion by the working muscle. Aerobic training also results in increased muscle blood flow, which is accomplished through elevated cardiac output (Ekblom and Hermansen, 1968) and an increased capillarisation of muscle tissue (Saltin and Rowell, 1980). Together, these enhancements facilitate an increased $\dot{V}O_2$ during high intensity exercise. Resulting in an ability to supply more energy through PCr re-synthesis and the aerobic system, decreasing the reliance on anaerobic glycolysis (Tomlin and Wenger, 2001). Thus, stemming the rise in H^+ and lowering of muscle pH during high intensity exercise (Sahlin and Henriksson, 1984). Based on the physiological mechanisms discussed it could be suggested that using the training load-fitness relationship established in Chapter 6 to facilitate an improvement in aerobic fitness, will subsequently attenuate the fatigue response from a given training load.

Studies investigating the relationship between aerobic fitness and fatigue have largely focused on the acute effects of exercise and the immediate recovery in the seconds and/or minutes after exercise. In contrast, few studies have established the time course of recovery in the hours and days after exercise, something that is of high importance given the increases in match frequency and limited recovery time between matches (Carling *et al.*, 2015). One such study (Johnston *et al.*, 2015) examined the influence of physical qualities, such as aerobic fitness and strength level, on markers of fatigue and muscle damage in the 48 h following a rugby football league match. They showed that in rugby league players, post-match decrements in CMJ peak power were lower in players with greater aerobic fitness (Yo-Yo IR1). This suggests that enhanced aerobic qualities allow faster recovery following intense intermittent exercise (McMahon and Wenger, 1998).

Within the literature a number of methods have been employed when looking to improve aerobic fitness in football players; long aerobic intervals (Helgerud *et al.*, 2001), high intensity intervals (Dupont *et al.*, 2004, Buchheit and Laursen, 2013a, Buchheit and Laursen, 2013b), RS training (Bravo *et al.*, 2008, Taylor *et al.*, 2015) and football specific SSGs (Impellizzeri *et al.*, 2006). A criticism of protocols such as Helgerud et al. (2001) long aerobic interval (4 x 4 minutes at 90-95% HR_{max}) intervention is the time it takes to complete. Although substantially shorter than continuous training, long aerobic intervals still detract significant time from technical and/or tactical training and substantially increase training volume. Chapter 6 has highlighted that weekly t>MAS is a key determinant when aiming to improve aerobic fitness. A novel training intervention would be to target a weekly t>MAS with a specific aerobic fitness improvement in mind, using the following equation:

$$\Delta \text{ aerobic fitness (\%)} = 0.7 * \text{weekly t>MAS} - 4.4$$

Supplementary training, such as 30s at MAS – 30s passive rest (30:30), adapted from the protocol extensively used by Billat et al. (1999, 2000, 2001), has been shown to increase the time athletes can spend around $\dot{V}O_{2max}$. This prolonged exposure to high intensity activity is likely to result in physiological adaptions, both centrally, via increased left ventricle size and wall thickness, and peripherally, via increased mitochondria size and volume plus increased skeletal muscle capillarisation. These changes in structure will result in increased stroke volume and subsequent cardiac output, also an increased maximal arterial-mixed venous oxygen difference, which are important determinants of $\dot{V}O_{2max}$ (Midgley *et al.*, 2006). This 30:30 protocol could easily be programmed alongside generic football training in order to increase the t>MAS experienced by players on a weekly basis.

7.1.1 Study aims

The aims of the present study were twofold. Firstly, to validate the concept of increasing weekly t>MAS in order to facilitate an improvement in aerobic fitness. This study will target a specific cumulative weekly time above MAS, based on the predicted improvement in aerobic fitness. Secondly, this study investigated the effect that the predicted improvements in aerobic fitness would have on the fatigue response, resulting from a standardised training session.

7.2 Methods

7.2.1 Study design

For this experimental research, players were allocated to either a MAS group (n = 7) or a RS group (n = 7) via stratified randomisation (Suresh, 2011) in order to balance the groups based on baseline aerobic fitness, measured via a 1500 m time trial. A RS intervention was selected as a positive control, due to its established effect on aerobic fitness (Taylor *et al.*, 2015). A traditional control group would not have been feasible given the elite standard of the participants used, it would not have been ethical to provide some players with an intervention and others not. All players completed a testing battery to assess MAS, MSS and post training fatigue response, following a standardised training session prior to (week 1) and post (week 7) a 5-week intervention (weeks 2-6). Data were collected over a 7-week period, during the late in-season competition phase (March-May).

7.2.2 Participants

Fourteen male youth football players (age: 17.6 ± 0.6 years, stature: 179.4 ± 5.4 cm, body mass: 72.5 ± 4.8) competing in the Under-18 Premier League agreed to participate in the present study. Before inclusion, players were examined by the club medical staff and were deemed to be free from illness and injury. Institutional ethics approval was granted prior to the commencement of the study (HLSJF270217) and conformed to the declaration of Helsinki. Informed consent was provided by all players and by their parents for players under 18 years of age.

7.2.3 Procedures

7.2.3.1 Physical performance

In order to assess training load via individualised speed thresholds, tests for MSS and MAS were conducted the start of the testing period. These measures were also assessed at the end of the 5-week intervention period and used as physical performance measures.

Maximum sprint speed and maximal aerobic speed

A 40 m sprint test was used to assess MSS as described in Chapter 3, Section 3.4.2.1. A 1500 m time trial was conducted to assess MAS as described in Chapter 3, Section 3.4.2.2. Reliability data for MSS and MAS is displayed in Chapter 4, Section 4.3.4 and Table 4.4.

7.2.3.2 Fatigue response

As part of the testing battery players fatigue response was assessed 24 h pre (baseline) and 24 h post a standardised training session as used in Chapters 5 and 6. An overview of the standardised training session can be found in Chapter 3, Section 3.4.4. For the present study, all players completed the same standardised training session pre (week 1) and post (week 7) the 5-week training intervention. A comparison of the training loads elicited from the standardised training sessions can be seen in Table 7.1. Based on their reliability, sensitivity and ability to detect a reproducible fatigue response the following measures were assessed; subjective fatigue and muscle soreness, DJ-RSI performance and accelerometer variables; PL_{ML} and $\%PL_{V}$.

Subjective wellness

Players' subjective ratings of fatigue and muscle soreness were collected as described in Chapter 3, Section 3.4.1.1. Reliability data is displayed in Chapter 6, Table 6.1.

Jump performance

Jump performance was assessed via DJ-RSI. Data were collected as described in Chapter 3, Section 3.4.1.2. Reliability data is displayed in Chapter 4, Section 4.3.2 and Table 4.3.

Sub-maximal shuttle run

A sub-maximal shuttle run was conducted as described in Chapter 3, Section 3.4.1.3. Based on their test re-test reliability and sensitivity to fatigue PL_{ML} and $\%PL_{V}$ were the variables used in this study. Reliability data is displayed in Chapter 4, Section 4.3.3 and Table 4.4.

7.2.3.3 Training intervention

As previously mentioned players were assigned to either a MAS or a RS intervention group. During the intervention all players completed the same training and match schedule, as prescribed by club coaches (4-5 training sessions per week and 1 competitive match per week). On top of their typical training, players completed one supplementary conditioning session per week depending on which group they were assigned to. Specifics for each training intervention are detailed below.

Maximal aerobic speed intervention

The MAS intervention was based on the findings of Chapter 6 – Part II and aimed to increase t>MAS to a level (13 minutes per week) that, based on the dose-response relationship previously established, would estimate an increase in aerobic fitness of approximately 4.7% or about three times the MDC in MAS. A graphical representation of how this intervention was programmed to increase t>MAS is depicted in Figure 7.1. Chapter 6 – Part II established a typical training week elicits around 7 minutes per week t>MAS. The supplementary MAS intervention would therefore need to produce, on average, an additional 6 minutes t>MAS in order to reach the target of 13 minutes per week.

$$\text{Slope} * \text{t>MAS} + \text{intercept} = \Delta \text{ aerobic fitness (\%)}$$

$$0.7 * \mathbf{13.0} + (-4.4) = \mathbf{4.7\%}$$

To achieve the additional mean weekly t>MAS of 6 minutes, the intervention was programmed in a progressive manner, over a 5-week period (Figure 7.1). Adapted from Billat *et al.* (2000) the intervention required players to perform a linear run at 110% of their individual MAS for 30-seconds followed by 30-seconds of passive recovery, with 2 minutes rest between sets. Players performed two sets of four repetitions, during the first week of the intervention. In each subsequent week the number of repetitions per set increased by one, resulting in the players completing two sets of eight repetitions in the final week of the intervention.

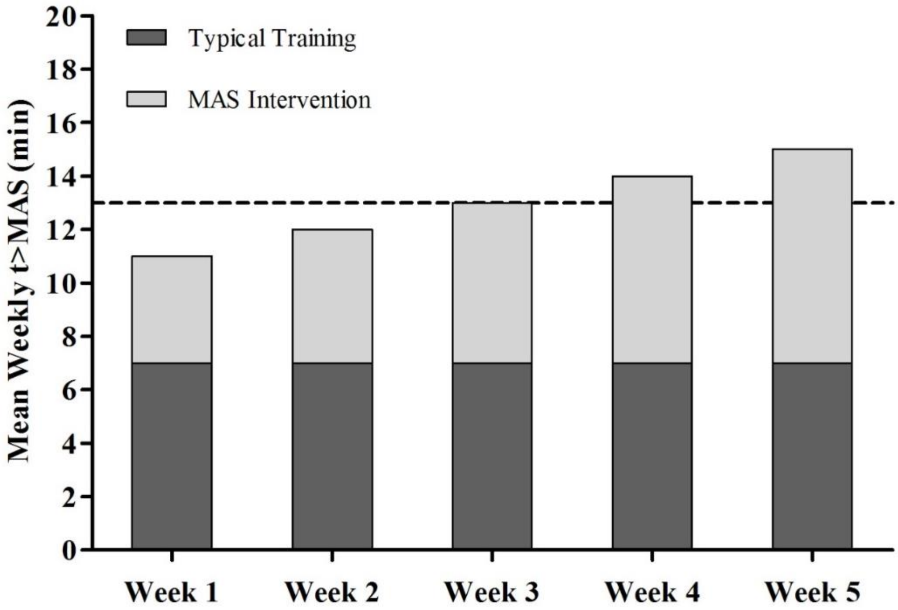

Figure 7.1. Graphical representation of the targeted t>MAS for the MAS intervention group. The dashed line represented the targeted mean weekly t>MAS of 13 minutes.

Repeated sprint intervention

The RS group performed 40 m maximum sprints at ~1:9 work: rest ratio, which is in accordance with previous research and has been shown to elicit improvements in aerobic performance (Yo-Yo IR1: ES = 0.61) (Taylor *et al.*, 2015). The sets and reps performed each week by the RS group were matched to the MAS group by number and time.

7.2.3.4 Training load monitoring

Training load was monitored throughout the study in accordance with the description in Chapter 3, Section 3.4.3. External training load variables collected in the present study were; TD, m>VHSR, m>SPR and t>MAS. Precision of the GPS signal throughout the study was; #sats: 13.8 ± 0.7; HDOP: 0.76 ± 0.11.

7.2.4 Statistical analysis

Visual inspection of histograms and Q–Q plots of raw data indicated no violation of normality assumptions. Raw data are therefore presented as the mean ± SD. Within and between group changes in fitness and fatigue response were compared via standardised changes in the mean (ES) using a custom spreadsheet (Hopkins, 2017). Uncertainty in these estimates were expressed as 90% confidence intervals (CI). The following criteria were adopted to interpret the magnitude of change; >0.2–0.6, small; >0.6–1.2, moderate; >1.2–2, large; >2, very large (Hopkins *et al.*, 2009). The chances of a clear effect being at least the observed magnitude or trivial was interpreted using the following scale of probabilistic terms: < 0.5% most unlikely; 0.5–5% very unlikely; 5–24.9% unlikely; 25–74.9% possibly; 75–94.9% likely; 95–99.4% very likely; ≥ 99.5% most likely (Batterham and Hopkins, 2006). The magnitude of change was classified as a substantial increase or substantial decrease when there was a 75% or greater likelihood of the effect being equal to or greater than the ES ± 0.2 (small). Changes were classified as unclear when there was a 5% or greater likelihood of the effect being both positive and negative (Hopkins *et al.*, 2009).

To understand the strength and direction of the relationship between the changes in fitness and changes in fatigue response, Pearson's product moment correlation coefficients (r) were calculated. The following criteria were adopted to interpret the magnitude of the relationship; 0.0-0.1 trivial; >0.1-0.3 small; >0.3-0.5 moderate; >0.5-0.7 large; >0.7-0.9 very large; >0.9-0.99 nearly perfect; 1.00 perfect (Hopkins *et al.*, 2009). Where the 90% confidence interval overlapped both the positive and negative threshold by ≥5% the relationship was deemed unclear (Hopkins *et al.*, 2009). Probabilistic inference was interpreted as stated above. If a relationship was classified as "substantial" a linear regression model was conducted to determine the level of variance in fatigue response explained by changes in fitness. The coefficient of determination (R^2) was calculated, along with intercept and slope values. Additionally, the minimum change in fitness required to elicit the MDC in fatigue response was calculated for each substantial relationship by rearranging the regression equation:

Training load to elicit MDC = MDC – Intercept / Slope

7.3 Results

During the 5 week intervention period three players sustained injuries unrelated to the intervention training program. As a result, the final analysis was conducted with five players in the MAS group and six players in the RS group. A total of 211 training and match files were analysed for the 11 players during the 5-week intervention period, the mean number of sessions per player was 19 (range: 17 – 21). All players completed all five prescribed conditioning sessions during the intervention period. Mean weekly training loads during the intervention period are shown in Figure 7.2. A substantially greater TD and t>MAS was completed by the MAS group, while the RS group completed substantially more m>SPR. Unclear differences in m>VHSR were observed. Excluding the intervention data, differences in training and match load were substantially greater for TD in the MAS group, all other differences were unclear.

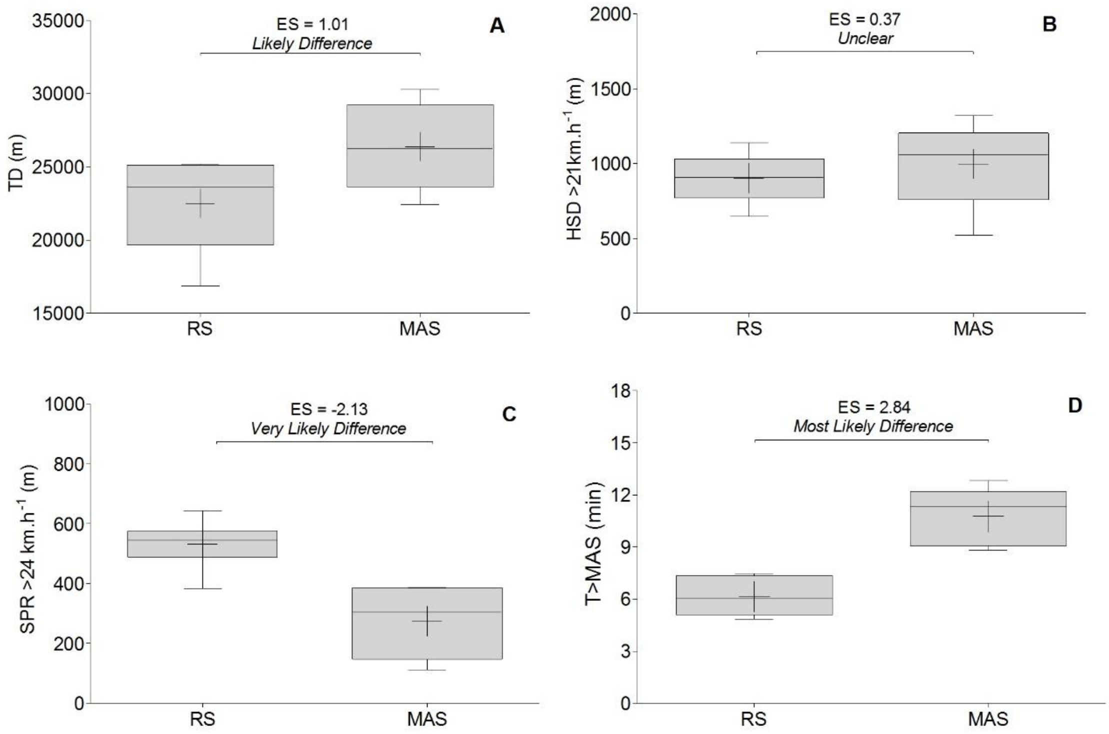

Figure 7.2. Training and match load over the 5-week intervention period for **A**) TD, **B**) m>VHSR, **C**) m>SPR and **D**) t>MAS. Box and whisker plots with median values, interquartile ranges and minimum and maximum values. + within each box plot represents the mean value.

7.3.1 Physical performance

7.3.1.1 Maximal aerobic speed

For aerobic fitness, observed changes within the MAS group showed a *likely improvement* (ES = 0.42; 90% CI 0.14 to 0.70) from 16.68 to 17.19 km.h^{-1} and the RS group were *very likely trivial* (ES = 0.11; 90% CI 0.02 to 0.20) changing from 16.51 to 16.64 km.h^{-1}. A *likely difference* between groups for ΔMAS (%) was observed (ES = 1.74; 90% CI 0.09 to 3.38) as shown in Figure 7.3. The observed difference in Δ MAS for the MAS group was 2.1 times the MDC (1.5%).

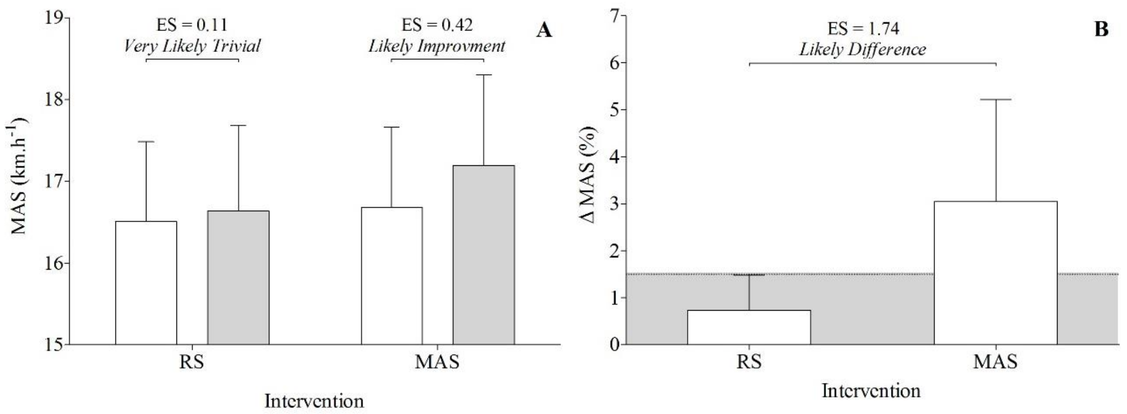

Figure 7.3. **A**) Between group changes in MAS (km.h^{-1}) pre (white bars) and post (grey bars) repeated sprint (RS) or maximal aerobic speed (MAS) intervention.
B) Within group changes in MAS (%). Grey shaded area represents the MDC (1.5%).

7.3.1.2 Maximum sprint speed

For MSS, observed changes within the MAS group saw a *possible improvement* (ES = 0.26; 90% CI -0.11 to 0.64) from 31.58 to 31.98 km.h^{-1} and within the RS group a *most likely improvement* (ES = 1.24; 90% CI 0.89 to 1.59) from 32.55 to 33.76 km.h^{-1}. A *likely difference* was observed between groups for Δ MSS (%) (ES = -1.23; 90% CI -2.27 to -0.19) as shown in Figure 7.4. The observed difference in Δ MSS for the RS group was 1.9 times the MDC (2.0%). Although a possible improvement was observed in the MAS this improvement was below the MDC.

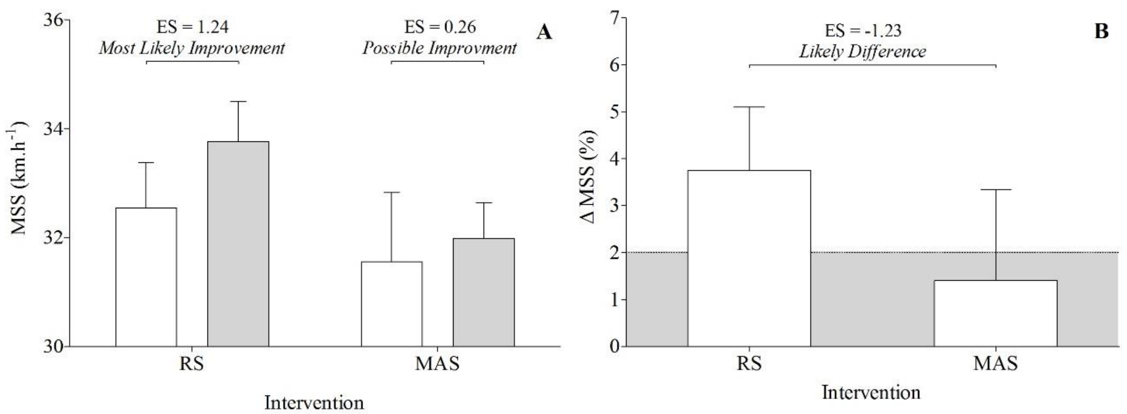

Figure 7.4. **A**) Between group changes in MSS (km.h^{-1}) pre (white bars) and post (grey bars) repeated sprint (RS) or maximal aerobic speed (MAS) intervention.
B) Within group changes in MSS (%). Grey shaded area represents the MDC (2.0%).

7.4.2 Fatigue response

7.4.2.1 Standardised training session

No clear within or between group differences in training load were found between the pre and post intervention standardised training sessions, used to induce a fatigue response (Table 7.1).

7.4.2.2 Subjective fatigue and muscle soreness

In response to the standardised training session, observed changes for subjective fatigue within the MAS group showed a *very likely improvement* (ES = 0.69; 90% CI 0.36 to 1.01) and within the RS group were *unclear* (ES = 0.05; 90% CI -0.49 to 0.60). There was a *very likely* between group difference for Δ subjective fatigue response (ES = 1.45; 90% CI 0.52 to 2.37) as shown in Figure 7.5. The observed difference for Δ subjective fatigue response for the MAS group was 1.1 times the MDC (10.6%).

Table 7.1. Within and between group differences in training loads during the standardised training sessions.

	RS Group			MAS Group			Between Group ES (MBI)	
	Pre	**Post**	**Within Group ES (MBI)**	**Pre**	**Post**	**Within Group ES (MBI)**	**Pre**	**Post**
TD (m)	8714 *(± 884)*	8842 *(± 658)*	0.12 ± 0.35 (*Unclear*)	9269 *(± 700)*	9273 *(± 738)*	0.01 ± 0.68 (*Unclear*)	0.58 ± 0.93 (*Unclear*)	0.51 ± 0.94 (*Unclear*)
VHSR (m)	536 *(± 124)*	545 *(± 150)*	0.06 ± 0.23 (*Likely Trivial*)	522 *(± 119)*	575 *(± 209)*	0.35 ± 0.96 (*Unclear*)	-0.10 ± 0.92 (*Unclear*)	0.14 ± 1.00 (*Unclear*)
SPR (m)	86 *(± 59)*	74 *(± 39)*	-0.17 ± 0.51 (*Unclear*)	55 *(± 11)*	61 *(± 34)*	0.44 ± 1.74 (*Unclear*)	-1.33 ± 2.13 (*Unclear*)	-0.29 ± 0.92 (*Unclear*)
t>MAS	4.7 *(± 0.9)*	5.0 *(± 0.5)*	0.23 ± 0.77 (*Unclear*)	5.5 *(± 1.1)*	5.4 *(± 0.8)*	-0.06 ± 0.73 (*Unclear*)	0.62 ± 0.94 (*Unclear*)	0.60 ± 1.18 (*Unclear*)

Note: TD; total distance, VHSR; very high speed running, SPR; sprinting, t>MAS; time above maximal aerobic speed, ES: effect size, MBI: magnitude based inference.

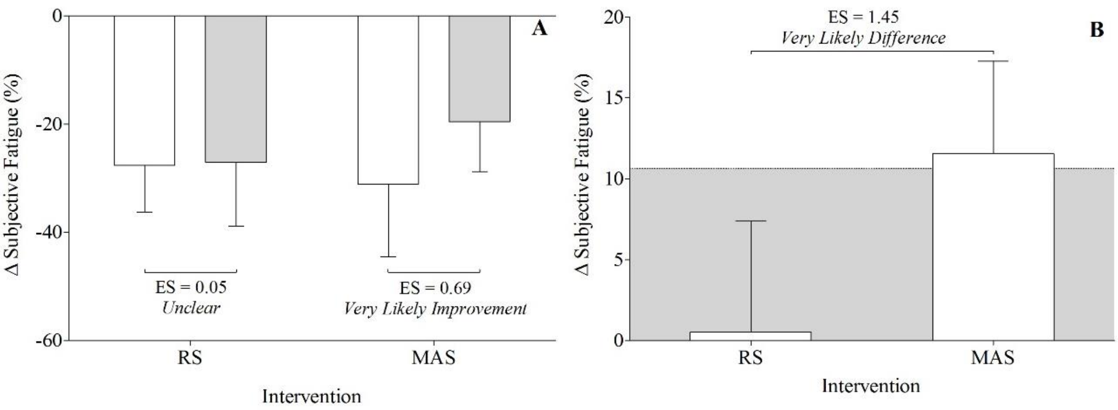

Figure 7.5. **A**) Between group changes in subjective fatigue response (%) pre (white bars) and post (grey bars) repeated sprint (RS) or maximal aerobic speed (MAS) intervention. **B**) Within group changes in subjective fatigue (%). Grey shaded area represents the MDC (10.6%).

In response to the standardised training session, observed changes for subjective muscle soreness, within the MAS group showed a *likely improvement* (ES = 1.38; 90% CI 0.12 to 2.63) and within the RS group were *unclear* (ES = 0.10; 90% CI -0.72 to 0.92). A *likely* between group difference for Δ subjective muscle soreness response was observed (ES = 0.80; 90% CI -0.13 to 1.73) as shown in Figure 7.6. The observed difference for Δ subjective soreness response for the MAS group was 1.6 times the MDC (8.5%).

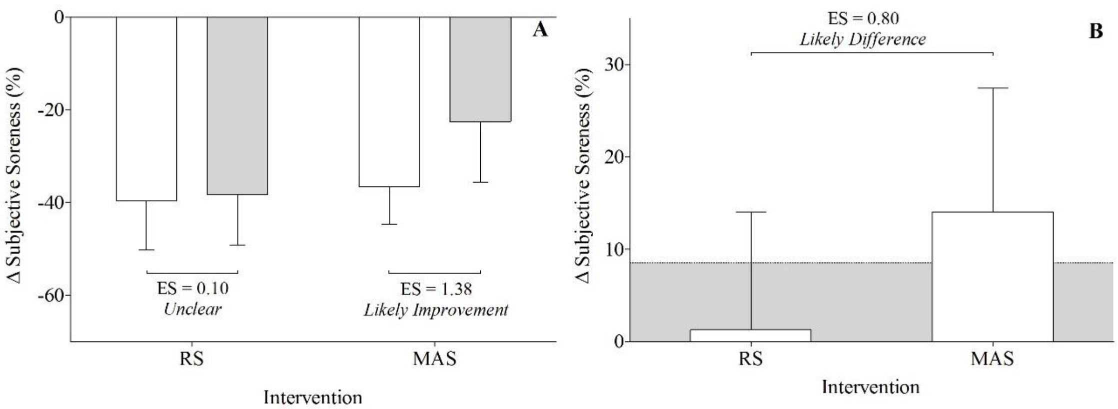

Figure 7.6. **A**) Between group changes in subjective muscle soreness response (%) pre (white bars) and post (grey bars) repeated sprint (RS) or maximal aerobic speed (MAS) intervention. **B**) Within group changes in subjective muscle soreness (%). Grey shaded area represents the MDC (8.5%).

7.4.2.4 Drop jump performance

In response to the standardised training session, observed changes for DJ-RSI within the MAS group showed a *very likely improvement* (ES = 1.59; 90% CI 0.62 to 2.55) within the RS group showed a *likely improvement* (ES = 0.49; 90% CI 0.00 to 0.97). Furthermore, a *likely* between group difference for Δ DJ-RSI response was observed (ES = 0.89; 90% CI -0.09 to 1.88) as shown in Figure 7.7. Although substantial changes were observed for both groups neither were above the MDC.

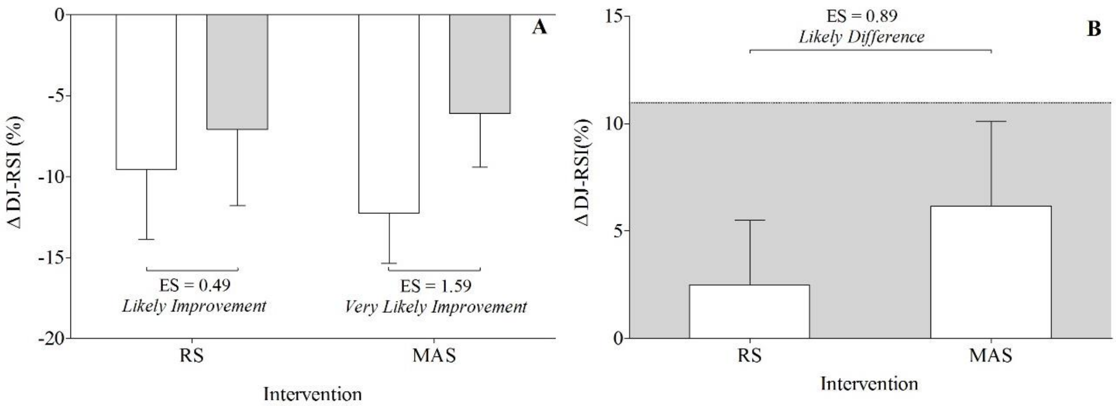

Figure 7.7. **A**) Between group changes in DJ-RSI response (%) pre (white bars) and post (grey bars) repeated sprint (RS) or maximal aerobic speed (MAS) intervention. **B**) Within group changes in DJ-RSI response (%). Grey shaded area represents the MDC (10.9%).

7.4.2.5 Sub-maximal shuttle run

In response to the standardised training session, observed changes in PL_{ML}, within the MAS group (ES = -3.45; 90% CI -7.51 to 0.60) were *unclear* and for the RS group were also *unclear* (ES = -0.95; 90% CI -2.74 to 0.83). An *unclear* between group difference for Δ PL_{ML} response was observed (ES = -0.38; 90% CI -1.32 to 0.55) as shown in Figure 8.8.

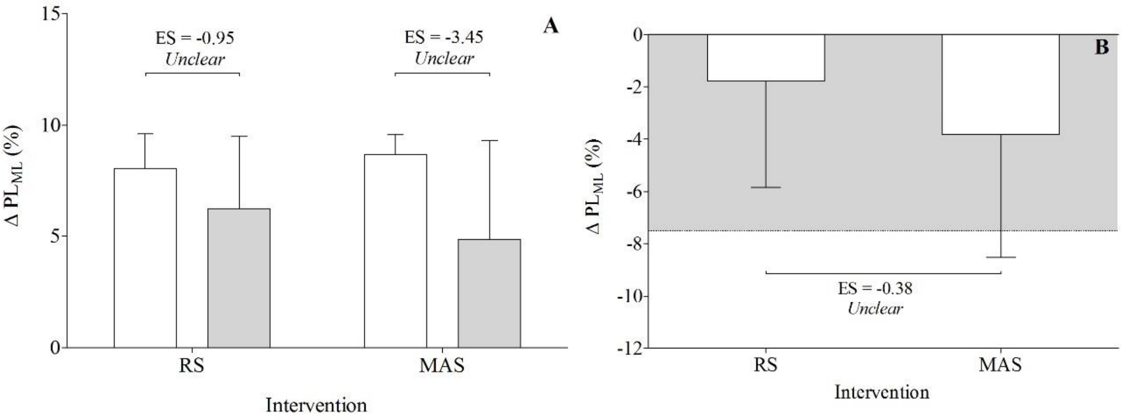

Figure 7.8. **A**) Between group changes in PL_{ML} response (%) pre (white bars) and post (grey bars) repeated sprint (RS) or maximal aerobic speed (MAS) intervention.
B) Within group changes in PL_{ML} response (%). Grey shaded area represents the MDC (7.5%).

In response to the standardised training session, observed changes in $\%PL_V$ within the MAS group showed a *most likely improvement* (ES = 2.09; 90% CI 1.79 to 2.39) and within the RS group a *likely improvement* (ES = 0.57; 90% CI 0.02 to 1.12). A *very likely* between group difference for Δ $\%PL_V$ response was observed (ES = 1.86; 90% CI 0.27 to 3.45) as shown in Figure 7.9. The observed difference for Δ $\%PL_V$ response for the MAS group was 1.1 times the MDC (3.9%).

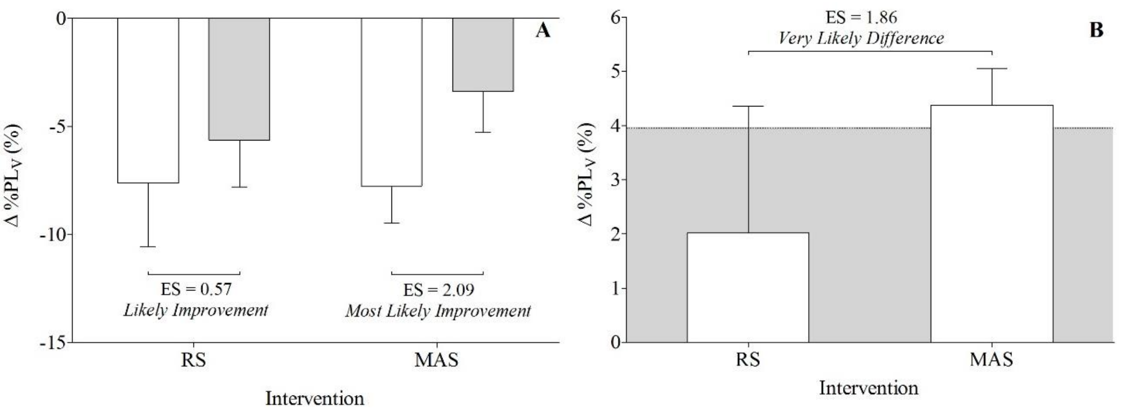

Figure 7.9. **A**) Between group changes in $\%PL_V$ response (%) pre (white bars) and post (grey bars) repeated sprint (RS) or maximal aerobic speed (MAS) intervention.
B) Within group changes in $\%PL_V$ response (%). Grey shaded area represents the MDC (3.9%).

7.3.4 Fitness – fatigue relationship

Substantial relationships were found between the percentage change in MAS and the percentage change in fatigue response for; DJ-RSI (r = 0.85; 90% CI 0.59 to 0.95, *likely large*), subjective fatigue (r = 0.84; 90% CI 0.56 to 0.95, *likely large*) and subjective muscle soreness (r = 0.80; 90% CI 0.48 to 0.93, *possibly large*) (Figure 7.10). Relationships between all other measures were unclear. This indicates that as MAS improves there is a linear attenuation of fatigue for these measures.

For the three substantial relationships linear regression models between changes in fitness measures and changes in fatigue response were calculated (Figure 7.10). These models specify the minimum percentage improvement in MAS required to elicit the MDC in fatigue response is 3.16% for subjective fatigue, 2.03% for subjective muscle soreness and 5.78% for DJ-RSI. This specifies the improvement in MAS that is required to attain a detectable improvement in fatigue response.

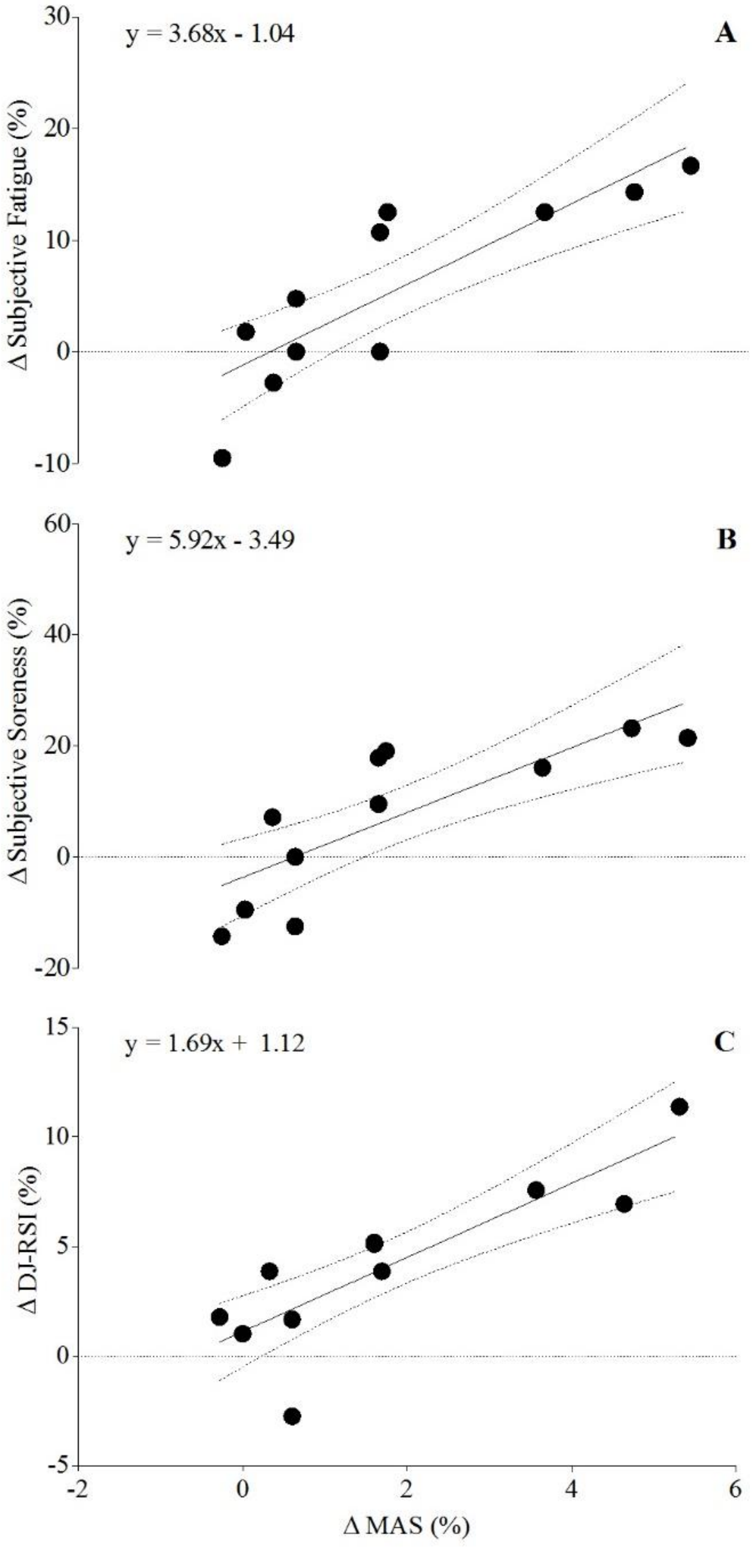

Figure 7.10. Relationships between percentage change in maximal aerobic speed (MAS) and changes in fatigue response for **A)** subjective fatigue, **B)** subjective muscle soreness and **C)** drop jump reactive strength index (DJ-RSI).

7.4 Discussion

The aims of the present study were twofold. Firstly, to compare the effects of two training interventions on measures of fitness; a novel MAS intervention, looking to increase time spent above MAS and a RS intervention. Secondly, to establish whether improvements in fitness might attenuate the fatigue response to a strenuous standardised training session. The main finding from this study is that aerobic fitness was substantially improved in the MAS group, and this improvement in aerobic fitness attenuated the fatigue response post a standardised training session in a group of elite youth football players. These findings validate the dose-response relationships established in Chapter 6, indicating that the prescription of weekly t>MAS can provide a predictable improvement in aerobic fitness and furthermore, this is associated with a predictable attenuation of fatigue.

Previous research has established the ability of various interventions to improve aerobic fitness in football players; long aerobic interval such as Helgerud *et al.* (2001) 4 x 4 minute intervention, high intensity intervals such as the 15:15 protocol at 120% MAS used by Dupont *et al.* (2004), RS training interventions (Bravo *et al.*, 2008, Taylor *et al.*, 2015) and football specific SSG programmes (Impellizzeri *et al.*, 2006). However, methodological differences, such as, training modality, training frequency and differences in the assessment of aerobic fitness make comparisons between studies difficult. Dupont *et al.* (2004) used a similar testing battery to the present study, assessing MAS and 40 m sprint time. They reported an 8% improvement in MAS and a -3.5% reduction in 40 m sprint time following 10 weeks of high intensity interval training (15:15 protocol). The greater percentage improvement in MAS seen in the study by Dupont *et al.* (2004) could be due to the longer intervention period (10 weeks versus 5 weeks) or possibly the lower starting level of aerobic fitness (16.1 $km.h^{-1}$ versus 16.7 $km.h^{-1}$).

This is the first intervention study that has used the dose-response relationship between t>MAS and changes in aerobic fitness (established in Chapter 6 – Part II) to prescribe weekly cumulative t>MAS in order to improve aerobic fitness. The present study found a *likely* improvement in aerobic fitness within the MAS group and a *likely* difference between intervention groups. This indicates that an intervention targeting increased t>MAS is practically useful for improving aerobic fitness over a short, 5-week in season period, when compared to a RS intervention. The lack of improvement in the RS contradicts the findings of a recent meta-analysis that indicated *possible moderate* improvements in Yo-Yo IR1 are seen following a RS training intervention similar to that used in the present study (Taylor *et al.*, 2015). The reason for this discrepancy might be the differences in methods used to assess aerobic fitness. It has been suggested that Yo-Yo IR1 performance can be determined by a range of different physical qualities, such as, aerobic and anaerobic fitness, sprint speed and change of direction ability (Mendez-Villanueva and Buchheit, 2013). Therefore, when targeting improvements in an isolated physical quality such as MAS, estimated from 1500 m time trial performance, a RS intervention might not be as effective as previously thought. On the other hand, a *most likely* improvement in MSS was observed for the RS group and a *likely* between groups difference. This shows that, while the expected improvement in aerobic fitness was not seen in the RS group a substantial improvement in MSS was observed. These findings highlight the importance for practitioners to select the appropriate intervention when looking to improve certain physical qualities within their squad of players.

A key component of this study was the programming of the MAS groups' intervention based on the dose-response relationship established in Chapter 6 – Part II. It was estimated that the MAS intervention, plus typical training and match load, would provide around 13 minutes per week t>MAS and this would increase aerobic fitness by around 4.7%. Findings indicate the MAS group completed, on average, around 10.8 minutes per week t>MAS (Figure 7.2). As all conditioning sessions were completed this discrepancy between planned and actual t>MAS might be due to differences in training and match load. Despite the lower than planned t>MAS, the improvement in aerobic fitness within the MAS group was 3.04%, this is very close to what would be predicted from a weekly t>MAS of 10.8 minutes (2.95%). This further highlights the predictable nature of the relationship between t>MAS, as a load measure, and improvements in aerobic fitness. Additionally, these data show how practitioners can use the information provided in Chapter 6 – Part II to inform their training programmes.

A novel aspect of this study was the assessment of a fatigue response following a standardised training session, similar to that used in Chapters 5 and 6. Results indicate a clear reduction in the fatigue response of the MAS group post intervention. Substantial between group differences were found for DJ-RSI, %PL_V and subjective ratings of fatigue and muscle soreness. This is the first study to document how an intervention improving aerobic fitness, can attenuate the fatigue response following training in football players.

Although the reasons behind the reduction in fatigue response were not assessed in the present study, it could be suggested that with an improvement in aerobic fitness the relative intensity of the standardised training session was reduced. Resulting in a reduced fatigue response for the same external workload. Various mechanisms could have resulted in this attenuation of fatigue; for example, an athlete with greater aerobic might exhibit an increased mitochondrial number, size, and surface area (Holloszy and Coyle, 1984) which will allow greater movement of pyruvate into the mitochondria, resulting in reduced lactate production. Also, increased concentrations of aerobic enzymes will enhance the capacity to generate ATP by oxidative phosphorylation during exercise. Furthermore, individuals with an increased MAS might have increased myoglobin concentrations (Saltin and Rowell, 1980). This would enhance the ability of the skeletal muscle to transport oxygen from the muscle cell membrane to the mitochondria and will increase the size of myoglobin oxygen stores, therefore increasing the delivery of oxygen to the mitochondria during exercise (Jones *et al.*, 2013). The adaptations that result from an improvement in aerobic fitness could therefore result in an ability to supply more energy through the phosphagen and aerobic systems, for the same external workload. Therefore, during the standardised training session post intervention players had less dependence on anaerobic glycolysis, resulting in less accumulation of H^+, maintenance of optimum muscle pH, and less interference with sarcoplasmic reticulum calcium release and cross-bridge cycling, resulting in greater maintenance of muscle force production (Metzger and Moss, 1990) throughout the training session. These mechanisms are likely the cause of the reduction in fatigue response from the same workload, observed in the present study.

A final novel finding is the association between changes in aerobic fitness and changes in fatigue response for DJ-RSI, subjective fatigue and muscle soreness. This indicates a dose-response relationship is present; the greater the improvement in aerobic fitness, the greater the potential reduction in fatigue response (Figure 7.10). This analysis also attempted to establish the change in aerobic fitness that is required to achieve the MDC for each fatigue measure. For example, to achieve a detectable improvement in DJ-RSI performance, a 5.8% improvement in aerobic fitness is required. This is of great importance to practitioners as it contributes to the understanding of what might be a minimum practically important change in aerobic fitness (Thorpe *et al.*, 2017). Findings from Chapter 6 – Part II would suggest that around 15 minutes per week t>MAS is required in order to gain a 5.8% improvement in aerobic fitness. This information can therefore assist practitioners in designing appropriate training programs that will produce a practically important change in MAS and in turn a detectable improvement in fatigue response.

7.4.1 Conclusion

This is the first investigation to examine the effect a novel method of prescribing a training intervention will have on aerobic fitness and the fatigue response following a standardised training session. This intervention prescribed weekly t>MAS based on the dose-response relationship established in Chapter 6. Clear, predictable improvements in aerobic fitness resulted from the 5-week MAS conditioning intervention, in comparison to trivial changes following a traditional RS intervention. Consequently, these improvements in aerobic fitness facilitated a clear attenuation of fatigue, following a standardised training session, for DJ-RSI, $\%PL_V$ and subjective measures of fatigue and muscle soreness. Furthermore, key practical recommendations such as the predictable nature of the training response, both in terms of improvements in aerobic fitness and the reduction in fatigue response have been highlighted.

7.5 Perspective

Chapter 6 of this thesis emphasised t>MAS as a key training load variable if practitioners are looking for accurate outcomes from their training programmes, with regards to fitness and fatigue. Furthermore, the need for careful manipulation of this measure was highlighted, given the known trade-off between fitness and fatigue. Increases in t>MAS are essential for improvements in aerobic fitness (Chapter 6 – Part II), however, large acute doses of t>MAS result in decrements in DJ-RSI performance, with concomitant increases in subjective fatigue and muscle soreness (Chapter 6 – Part I). Training load must therefore be carefully manipulated in order to mitigate the accumulation of fatigue, particularly in-season.

This chapter set out to address the need for empirical evidence surrounding the relationship between improvements in aerobic fitness and the attenuation of fatigue in football players. Previous research suggested that improvements in aerobic fitness might reduce the fatigue associated with high intensity exercise (Tomlin and Wenger, 2001) however, research specific to football players is lacking. Furthermore, no research to date has assessed if interventions that improve aerobic fitness can also attenuate a fatigue response. Chapter 7 therefore, looked to perform a novel intervention, that used the evidence from Chapter 6 – Part II, targeting a specific t>MAS to elicit a predicted improvement in aerobic fitness. Results from Chapter 7 indicate a highly predictable improvement in aerobic fitness from the training load that was completed during the study, validating the use of the t>MAS as a monitoring tool. Additionally, this improvement in aerobic fitness attenuated the fatigue response following a standardised training session, a feature used repeatedly throughout this thesis (Chapters 5 and 6). The final key finding was the very strong relationship between improvements in aerobic fitness and reductions in fatigue response. This further highlights the importance of aerobic fitness in relationship between training load and fatigue, demonstrating that for a given t>MAS one can estimate the improvement in aerobic fitness and subsequently estimate the reduction in fatigue response.

CHAPTER 8

8.0 Synthesis of Findings

8.1 Synthesis

The purpose of the following chapter is to discuss the present findings in relation to the original aims and objectives of this research programme. A synthesis of findings will be presented in relation to current literature and how these findings have contributed to the existing body of knowledge. Practical recommendations to optimise the prescription and monitoring of training load and fatigue in elite youth football players will be discussed, based on the major findings from this thesis. The limitations of the present programme of research will be acknowledged before making recommendations for future research based on the current thesis and the evolution of football training methods, statistical analysis and technologies in recent years.

8.2 Achievement of Aims and Objectives

Applied research within football continues to investigate methods of monitoring both training load and training response. The advancement in technology in recent years has increased the ability to monitor and assess athletes (Akenhead and Nassis, 2016, Weston, 2018). However, with this increase in monitoring comes a need to understand the validity, reliability and sensitivity of the assessment tools, how these tools relate to specific training outcomes and finally how these tools can have a positive impact on the training process.

The main aim of this thesis was therefore to establish the most appropriate methods for quantifying both training load and training response, to investigate how these measures interact via the dose-response relationship, and finally how these findings can help to inform the training process, through individualised training interventions, within an elite youth football academy. This aim was met through the completion of 5 separate studies (Chapters 4, 5, 6 and 7) investigating the following objectives:

Objective One: To determine the most appropriate methods for assessing fatigue in an applied environment by establishing the test-re-test reliability, sensitivity and reproducibility of potential fatigue monitoring measures. *(Chapters 4 and 5)*

In order to determine the most appropriate methods for assessing fatigue a three stage approach was employed that assessed the reliability, sensitivity and reproducibility of potential fatigue monitoring measures (Figure 8.1). This objective was met in Chapters 4 and 5. Firstly, test re-test reliability was established in Chapter 4 and values for the minimum detectable change (MDC) calculated for tri-axial accelerometer measures collected during a submaximal shuttle run, various assessment of jump performance and for subjective wellness measures.

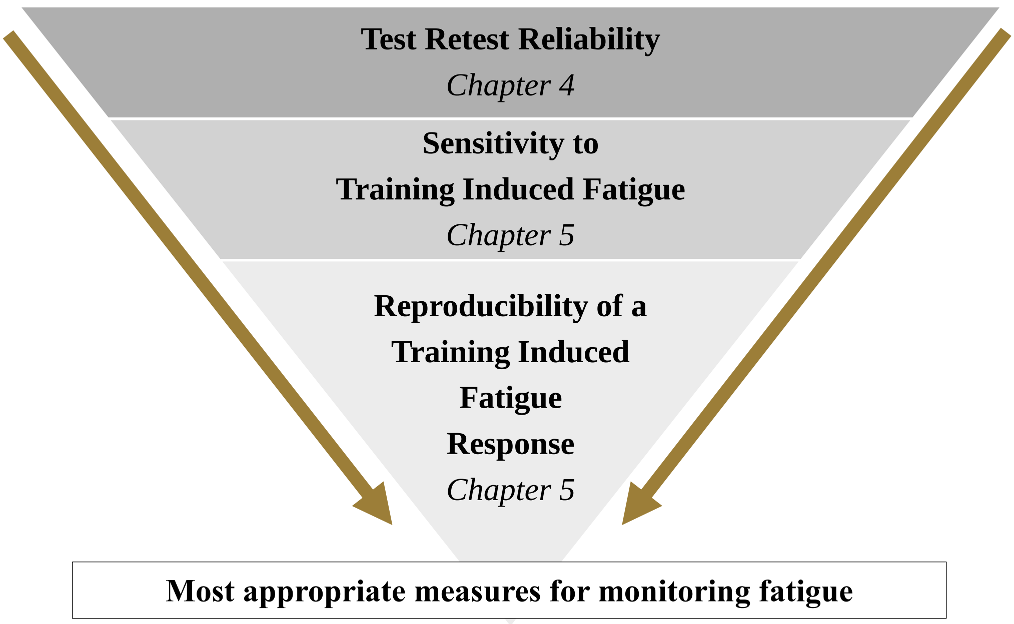

Figure 8.1. Schematic of the three staged approach used to select the most appropriate methods for assessing fatigue in an applied environment.

Chapter 5 then built upon this by assessing if, following a strenuous standardised training session changes in these measures exceeded the MDC. This would determine if the “signal” (changes following strenuous training) was greater than the “noise” (test re-rest MDC). If the signal is greater than the noise then a measure is deemed to have appropriate sensitivity. Finally, Chapter 5 repeated this method over two consecutive weeks to establish the reproducibility of this fatigue response. Only of an assessment was deemed sensitive and reproducible would it be considered for use in subsequent chapters. Five measures were therefore highlighted as the most appropriate for use in a practical environment; subjective fatigue and muscle soreness, DJ-RSI and tri-axial accelerometer variables PL_{ML} and $\%PL_{V}$.

Objective Two: To examine the dose-response relationship between training load, fitness and fatigue, with special reference to the use of individualised external training load. *(Chapter 6)*

Following on from the findings of Chapters 4 and 5 it was important to understand how these measures of fatigue change following different doses of training load and also how more chronic changes in training load can influence a football players’ fitness levels. This objective was met in Chapter 6 – Part I and II. An important aim for this chapter was to assess differences in the dose-response relationships when using various training load measures, in particular, differences between arbitrary and individualised speed thresholds. It was hypothesised that an individualised external training load measure would display a stronger dose-response relationship, compared to arbitrary measures, given its association with a players’ individual physiological characteristics. The results of Chapter 6 suggest that an individualised measure of external training load, that takes into consideration the time each player spends above their maximal aerobic speed (t>MAS) has strong associations with both acute fatigue and chronic changes in fitness.

This finding demonstrates that t>MAS is a key measure of training load that must be monitored carefully by practitioners if they are to increase chronic training loads in order to improve fitness whilst not accumulating acute fatigue on a daily basis.

Objective Three: To investigate the efficacy of a training intervention to improve aerobic fitness and subsequently examine its ability to attenuate a fatigue response. *(Chapter 7)*

Considering the outcomes of Chapter 6, an intervention study was conducted in order to firstly assess the efficacy of a training programme that systematically increased chronic t>MAS, to improve aerobic fitness. Secondly, to investigate if these improvements in aerobic fitness contributed to the reduction of a post training fatigue response. These objectives were clearly met in Chapter 7. Players were assigned to either an intervention group targeting increased weekly t>MAS or a RS intervention group. Both interventions were conducted alongside players' training and match schedule over a 5-week period. Findings demonstrate that clear improvements in aerobic fitness were observed in the t>MAS group and clear improvements in sprinting speed in the RS group, highlighting the importance of specificity when selecting an appropriate training intervention. Furthermore, the improvements in aerobic fitness clearly attenuated the post training fatigue response. These findings suggest that an intervention targeting increased t>MAS is an effective way of improving aerobic fitness and subsequently reducing the amount of fatigue that is accumulated from a given training load.

8.3 General Discussion

This research programme investigated the effectiveness of an individualised method of monitoring and prescribing training to improve fitness and attenuate fatigue in elite youth football players. The main findings were that an individualised method of monitoring training load (t>MAS) displayed the strongest associations with both acute fatigue 24 h post training and longitudinal improvements in fitness over a 5-week training period. Furthermore, when this individualised method was used to prescribe training load, a clear, predictable improvement in aerobic fitness was evident. Most notably, this is the first research project to document that following this improvement in aerobic fitness, players fatigue response, 24 h post training, was substantially reduced.

The exact mechanisms behind this improvement in fatigue response were not assessed during this study. However, it is fair to suggest that the attenuation in fatigue response occurred as a result of reduced relative intensity of the standardised training session following an improvement in aerobic fitness. This means that for the same external workload, players with greater aerobic fitness accumulated less fatigue within the standardised training session, post intervention. This has important implications for practitioners. It has been suggested that individuals with greater aerobic capability display increased concentrations of aerobic enzymes, increased mitochondrial number, size and surface area (Holloszy and Coyle, 1984, Jones and Carter, 2000). Together, these adaptations contribute to improved oxygen utilisation. Aerobic training has also been shown to result in increased muscle blood flow, which is accomplished through elevated cardiac output (Ekblom and Hermansen, 1968) and increased capillarisation of muscle tissue (Andersen and Henriksson, 1977). These enhancements result in an increased $\dot{V}O2$ during training (Ekblom *et al.*, 1968). The adaptations that result from an improvement in aerobic fitness could therefore result in an ability to supply more energy through the phosphagen and aerobic systems. Thus, decreasing the dependence on anaerobic glycolysis, resulting in less accumulation of H^+, maintenance of optimum muscle pH, less interference with sarcoplasmic reticulum calcium release and cross-bridge cycling, resulting in greater maintenance of muscle force production (Metzger and Moss, 1990). In addition to acidosis, anaerobic metabolism in skeletal muscle also involves hydrolysis of creatine phosphate to creatine and Pi. Creatine has little effect on contractile function, whereas Pi, is thought to be an important cause of fatigue during high intensity exercise (Westerblad *et al.*, 2002). Increased Pi substantially impairs myofibrillar performance, decreases sarcoplasmic reticulum calcium release and therefore contributes to the decreased activation of the muscle (Allen and Trajanovska, 2012). These physiological mechanisms could be applied to the results of Chapter 7, furthermore, highlighting to practitioners the importance of considering the aerobic fitness of football players, not only from a performance perspective, but also from a fatigue perspective. If players are able to tolerate greater training loads throughout the training week they will be able to spend a greater about of time working on technical and tactical performance, something that could have great benefits particularly in an elite football academy.

Another novel finding from this thesis was the ability to prescribe training based on t>MAS, resulting in a predictable improvement in aerobic fitness. This highlights that practitioners should carefully monitor and target increased t>MAS if an improvement in aerobic fitness is the desired outcome of their training programme. Chapter 7 utilised a running intervention whereby players ran for 30 seconds at 110% of their MAS followed by 30 seconds of passive recovery, this was adapted from previous work by (Billat *et al.*, 2000). The time cost of this intervention was around 8 to 16 minutes per week, this is substantially less than other interventions such as the 4 x 4 minutes protocol utilised by Helgerud *et al.* (2007). Again, this then allows more time for technical and tactical development throughout the training week. Another interesting finding from Chapter 7 was the substantial improvement in MSS observed in the repeated sprint group. It is possible that the 1:9 work to rest ratio, although within guidelines (Taylor *et al.*, 2015), was too high to elicit improvements in aerobic fitness. However, the greater rest between sprints has facilitated clear improvements in sprint speed. This highlights the importance of specificity within the training programme. Physical assessments such as the 1500m time trial and 40 m sprint test conducted throughout this thesis should be used to complete a locomotor profile of each player and identify areas for development. Players can then be assigned to either an MAS group or an MSS group based on their individual physical development needs. If improvements in both areas are required previous research by Dupont *et al.* (2004) has shown a 15:15 protocol at 120% MAS resulted in improvements in both aerobic fitness and sprint speed.

As well as investigating the ability to monitor and prescribe training to estimate changes in fitness another important objective within this thesis was to establish the ability to monitor and prescribe training to estimate changes in fatigue. It was hypothesised that an individualised external training load measure (t>MAS) would display the strongest dose-response relationship between training load and fatigue. Two previous studies have assessed the relationship between external training load and fatigue in football (Scott and Lovell, 2017, Thorpe *et al.*, 2015). Thorpe *et al.* (2015) found a *large* relationship between arbitrary high speed running (>14 $km \cdot h^{-1}$) and subjective fatigue however, objective measures; CMJ and HRV displayed trivial to small relationships. A potential explanation could be that training load was not sufficient to induce a fatigue response in these objective measures. In agreement with this notion, results in Chapter 6 – Part I showed a greater training load is required to elicit the MDC in objective measures compared to subjective measures. For example, the t>MAS required too elicit the MDC in subjective fatigue is 2.0 min, in contrast the t>MAS required to elicit the MDC in DJ-RSI performance is 5.6 min. This indicates that from a small amount of t>MAS players perceive a substantial level of subjective fatigue however, 5.6 minutes above MAS can be completed in training before physical performance shows a detectable change. This has multiple important implications for practitioners. Firstly, it highlights the need to conduct both objective and subjective assessments in order to gain a full understanding of an athletes fatigue status. This might lead to informal education with individual players around sensations of fatigue and how these perceptions can influence physical performance. Secondly, it highlights that if only subjective assessments are used training modifications based on these measures might lead to an overly cautious approach, whereby training load is reduced given the substantial levels of subjective fatigue when objectively players' physical performance is at an optimal level. This could lead to unnecessary reductions in training load and ultimately under training that might negatively affect performance and increase injury risk (Gabbett, 2016).

Scott and Lovell (2017) expanded on the work of Thorpe *et al.* (2015), by assessing both individualised and arbitrary measures of training load. Scott and Lovell (2017) found only small relationships between training load and subjective fatigue, with no differences between arbitrary and individualised training load measures. However, a major criticism of this study is that no objective assessments of fatigue were completed. The results of Chapter 6 – Part I indicated a *large* to *very large* relationship between training load and changes in DJ-RSI performance, subjective fatigue and muscle soreness and *moderate* relationships with $\%PL_V$. However, in agreement with Scott and Lovell (2017) no differences were found between arbitrary and individualised measures. It is possible that the large multicollinearity (see Appendix E) between training load measures following an acute training session is the reason for the lack of differences observed between arbitrary and individualised measures. This is likely a common issue with this type of data as a large number of training load variables are displaying covariance with each other. A potential solution might be to conduct a principle component analysis as descripted by Weaving *et al.* (2019). This dimension reduction technique can be used to assess large data sets. It will reduce the number of variables analysed and the covariance within the data, whilst maintaining the maximum amount of information within each principle component, therefore allowing multivariate analysis to be conducted.

Another real strength to this thesis was the rigorous approach used to determine suitable methods of assessing fatigue in the applied environment (Figure 8.1). The approach used allows for the reliability (noise) and the sensitivity (signal) to be assessed before decisions are made about the usefulness of any measure. Previous literature has tended to use a criteria based approach for decisions around reliability, with thresholds of 10% for CV and 0.80 for ICC typically used (Cormack *et al.*, 2008b, Beattie and Flanagan, 2015, Roe *et al.*, 2016). Although this criteria based approach might aid in the decision making process around measurement error it is our opinion that reliability data should only be assessed alongside an estimate of measurement sensitivity. With this method researchers can be more confident that the signal of the measure is greater than the noise and therefore the measure can be used with confidence in future research and in the applied setting. With the aforementioned criteria based approach certain measures might display a CV < 10%, however, if sensitivity is low, this will make it very difficult to detect meaningful changes in future studies. In contrast if a measure displays a CV > 10% it might be deemed unreliable and therefore inappropriate for future research. However, if sensitivity data suggests the signal of this measure is around 20-30% this might actually make it a useful measure. In summary, the methodology used within this thesis to select appropriate measures utilises the signal to noise ratio. This can be used to identify measures that are capable to detecting meaningful changes in future research and is a more robust method than the popular criteria based assessments of reliability.

The MDC was used extensively throughout this thesis as a threshold for detectable changes in each outcome measure. As was discussed in previous chapters this is seen as a more stringent measure of test re-test reliability as it constructs a confidence level around the typical error of measurement. However, another important consideration when making decisions around the magnitude of change is the minimum practical important change (MPIC) (Atkinson, 2003, Thorpe *et al.*, 2017). It is important to consider that the MDC might not be the same as the MPIC. The MDC is the smallest true change that has a reasonable probability of being substantial in a well enough powered study, however, this change might still not be practically important. The selection of an MPIC is however difficult in a multifactorial sport such as football, where it is not straight forward to attribute changes in a physical/ physiological measure with on pitch performance. One method for calculating a MPIC is the “anchor” method. In the “anchor” approach, the measurement (or change in measurement) is anchored to an associated change in another outcome measure, the anchor variable. A change in fatigue status could be anchored to changes in illness, soft-tissue injury, or physical match performances. To give a theoretical example, the MDC for DJ-RSI is 10.9%, this means that if a change of this magnitude occurs we are 75% confidence that a real change has occurred, given the known within-subject variability in this measurement. However, theoretically the MPIC for DJ-RSI could be 20% as a reduction in DJ-RSI performance of this magnitude relates to a 10% increase in injury risk. Although this is a theoretical example it is important that researchers and practitioners attempt to quantify not only the MDC but also the MPIC. To investigate the MPIC for the outcome measures used in this research programme was beyond the scope of this thesis. Nonetheless, future research should strive to quantify such thresholds through prognostic-longitudinal type research (Hemingway *et al.*, 2013, Finch and Marshall, 2016).

8.3.1 Conclusion

In conclusion, this research programme has been the first to establish that an individualised approach to monitoring and prescribing training can be an effective means of improving aerobic fitness, which in turn attenuates the fatigue response for a given training load. The relationship between training load, fitness (Akubat *et al.*, 2012, Manzi *et al.*, 2013) and fatigue (Thorpe *et al.*, 2015, Scott and Lovell, 2017) has previously been investigated. However, no study has assessed these relationships concurrently, using the same training load measures. This thesis has highlighted that an individualised approach to monitoring and prescribing training, via the assessment of t>MAS, can provide novel information with regards to the relationship between training load, fitness and fatigue. Furthermore, the new knowledge gained throughout this thesis has important applications for practitioners. Clear methods have been documented with regards to how the monitoring and prescription of training load can be utilised on an individual basis. Firstly, to consider the acute effects of training load on fatigue, and secondly, the chronic effects on fitness and finally, how improvements in fitness can facilitate the attenuation of fatigue. This thesis has documented the importance of assessing both reliability and sensitivity in order to make decisions on the usefulness of a fatigue or physical performance measure, and the need for future research to investigate the MPIC in these outcome measures.

8.4 Practical Applications

The experimental studies that comprise this thesis have a very high level of applicability to practitioners. It is hoped that the novel information gained throughout this thesis will provide practitioners with a greater understanding of the relationship between training load, fitness and fatigue and assist with the prescription and monitoring of training in their daily practice.

Decision making based on the MDC

A challenge for any practitioner is to quickly and effectively establish the physical state of a group of players prior to the start of each training session. Training preparation, prescription and subsequent recovery strategies might hinge on the results of pre training fatigue assessments. They therefore need to be time efficient, easy to analyse, valid, reliable and sensitive in order for practitioners to assist in the decision making process. The key practical application of the findings from Chapters 4 and 5 is the use of the MDC, that can be used as a threshold for changes that are considered “real” (Charter, 1996, Weir, 2005). For example the MDC for $\%PL_V$ established in Chapter 4 is 3.9%, this stipulates that an increase greater than 3.9% must be achieved before a change is greater than the measurement error and can be considered real (at a 75% confidence level). Using this statistical approach can enhance the decision making process for practitioners by quickly highlighting individuals who fall outside of the MDC. This might lead to timely interventions, such as, further discussion with the player, recovery interventions and/or training load modifications. Finally, a 75% confidence level for the MDC was selected to be used throughout this thesis based on the applied nature of the research programme. However, if a more stringent approach is warranted then an 85% or 95% confidence level could be calculated. Using the example of $\%PL_V$ this would have resulted in MDCs of 4.9% or 5.6% respectively.

Estimating the fatigue response to training

Another practical application is the ability to estimate fatigue from a given training load based on the relationship between training load and fatigue, established in Chapter 6 – Part I. This could enhance a practitioner's ability to plan appropriate training loads, subsequently improving the training process. For example, if the planned t>MAS for a given session is six minutes, the decrement in DJ-RSI performance can be estimated based on the model parameters presented in Chapter 6:

$$\text{slope} * \mathbf{t{>}MAS} + \text{intercept} = \Delta\ \text{DJ-RSI}\ (\%)$$

$$-3.7 * \mathbf{6.0} + 10.0 = -12.2$$

This estimates the decrement in DJ-RSI performance, 24 h post training will be -12.2%. This would indicate a large amount of fatigue will result from this session, depending on where this training session falls within the overall program, the practitioner might look to adapt the t>MAS for this session to reduce the predicted fatigue response.

Estimating the fitness response to training

In a similar manner to estimating the fatigue response, the ability to accurately estimate aerobic fitness responses based on weekly t>MAS is a key finding from this thesis. Practitioners can again use the linear regression model parameters, intercept (-4.4), slope (0.7) and SEP (1.0), to estimate the aerobic fitness response from weekly t>MAS. For example, if the targeted t>MAS for a 6-week training period is 12 minutes per week.

Using the following equation:

$$\text{slope} * \mathbf{t{>}MAS} + \text{intercept} = \Delta\ \text{aerobic fitness}\ (\%)$$

$$0.7 * \mathbf{12.0} + (-4.4) = 4.0$$

This predicts an improvement in aerobic fitness of +4.0% (±1.0%). This highlights the predictive value of t>MAS as a training monitoring and prescription tool and how practitioners can use the results established within Chapter 6 – Part II to monitor weekly t>MAS, with a clear, predictable physiological response as the outcome measure.

Relationship between improvements in aerobic fitness and the attenuation of fatigue

A further practical application is the novel finding from Chapter 7 that a clear linear relationship exists between changes in aerobic fitness and changes in fatigue response for DJ-RSI, subjective fatigue and muscle soreness (see Figure 7.10). This indicates that improvements in aerobic fitness reduce player fatigue in a predictable manner, giving further evidence to the relationship between fitness and fatigue. Practitioners can use this information to help target specific improvements in aerobic fitness that will result in detectable reductions in fatigue response. Again, by using the linear regression parameters established for this relationship in Chapter 7, practitioners can estimate the reduction in fatigue response from a specific improvement in aerobic fitness. For example, the MDC for DJ-RSI is 10.9%, to understand the improvement needed in aerobic fitness to facilitate this reduction in DJ-RSI response, the following equation can be used:

$$(\textbf{targeted } \boldsymbol{\Delta} \textbf{ DJ-RSI response} - \text{intercept}) / \text{slope} = \Delta \text{ aerobic fitness required}$$

$$(\mathbf{10.9} - 1.1) / 1.7 = 5.8$$

This suggests that an improvement in aerobic fitness of +5.8% is required to elicit a 10.9% reduction in the fatigue response following a standardised strenuous training session. Furthermore, this statistical method can be used for other variables that displayed a similar relationship i.e. subjective fatigue and muscle soreness (Figure 7.10).

8.5 Main Limitations of Findings

Limitations associated with this thesis should be considered within the context of the elite sporting environment that the research was conducted. Small sample sizes and limited opportunities to manipulate training programmes are inherent issues when conducting research of this nature. It is noteworthy that while certain limitations are apparent, the studies conducted as part of this thesis have had unprecedented ability to standardise training sessions, manipulate training variables and to conduct training interventions.

Firstly, with regards to the assessment of reliability in Chapter 4, the relatively small sample sizes used might lead to greater error associated with the statistics presented. However, the sample sizes are specific to the elite football environment. A typical squad within an elite youth academy will consist of around 15-20 players, therefore reliability statistics are representative of the sample size which was used in subsequent experimental chapters. Furthermore, power estimations conducted as part of Chapter 4 indicated that a sample size of 9-10 players would be deemed acceptable for all outcome measures, this was exceeded in all studies apart from Chapter 7 which had seven players per group.

It has been suggested that greater than two trials are required to provide a more accurate representation of the systematic error that could exist in each measure (Hopkins, 2000). However, the use of two trials has been used repeatedly within the literature (Buchheit and Mendez-Villanueva, 2013, Roe *et al.*, 2016). Furthermore, the test re-test design of the reliability studies provides practitioners with valuable insight into the reproducibility of said measures.

Given the relatively small sample sizes and single cohort designs some caution must be taken when generalising the results from this thesis. Particularly; for example, when assessing the dose response relationship between training load and fitness in Chapter 6 – Part II. This model was create using data from a sample of 14 players, from one Academy squad, over a 6 week period and although it was validated as an effective method of improving aerobic fitness, with this cohort of players, in Chapter 7, in order to generalise these findings to a wider population, more data might need to be collected. Future research should look to complete a replication study with a larger sample of players, from multiple Academies, across a range of age groups. Furthermore a study with more than one observation per player of the course of a competitive season would be warranted.

Chapter 6 – Part I looked to investigate the relationship between training load and a fatigue response. A rigorous methodological approach was used in order to assess players via a randomised crossover design, something which was lacking from previous dose-response studies (Thorpe *et al.*, 2015, Scott and Lovell, 2017). In order to complete this type of research in an applied environment however, the number of observations that could be completed was limited to three (the minimum needed in order to conduct the within subject models used). This limited the analysis to only complete mixed *linear* models, however, conceptually the training load-fatigue relationship might be more *curve-linear*. Future research could look to replicate this study with a greater number of observations, allowing a greater range of models to be fit to the data.

It might be noted that there are a lack of physiological response measures when assessing both fatigue and fitness. This could be seen as a limitation throughout this thesis. For example, assessments of jump performance were used as surrogate measures of neuromuscular fatigue and the average speed during a 1500 m time trial used as an estimate of MAS. However, these decisions were always based on the evidence of previous mechanistic studies that have shown these practical assessments to be valid estimates of physiological responses for both fatigue (Brownstein *et al.*, 2017, Thomas *et al.*, 2017) and fitness (Lorenzen *et al.*, 2009, Bellenger *et al.*, 2015). On a spectrum from mechanistic to applied research this is very much an applied body of work. It was very important throughout that the measures used, whilst evidence based, are also practically applicable in the elite sporting environment.

8.6 Recommendations for Future Research

The results of this thesis have made a considerable contribution to the existing literature surrounding the monitoring and prescription of training in football players, however, a number of opportunities for future research have been identified.

One of the major findings of this thesis is the established relationship between training load, specifically t>MAS, and fitness and fatigue. Another important consideration is the relationship between training load and injury risk, something which has received extensive research in recent years (Gabbett, 2016). However, current research has mainly focused on perceived training loads (Rogalski *et al.*, 2013), TD covered (Colby *et al.*, 2014) and arbitrary speed thresholds (Bowen *et al.*, 2017). Given the link between t>MAS, fitness and fatigue, longitudinal analysis of the association between t>MAS and injury risk is warranted.

A metric which has gained huge popularity in recent years is the acute: chronic workload ratio (Gabbett, 2016). This metric is the ratio between acute training load (typically 7 days) and chronic training load (typically 28 days). However, it has now been shown that assessing training load in this manner can lead to erroneous assumptions about a players training status (Lolli *et al.*, 2017, Lolli *et al.*, 2018). A possible solution might be to build upon the information gained throughout this thesis and develop a systems modelling approach. Developed originally by Banister *et al.* (1975) and later adapted by Morton *et al.* (1990) and Busso *et al.* (1991) this type of approach uses training load to estimate fitness and fatigue on an individual basis. Using parameters such as weighting factors and decay constants, performance at any given time can be estimated. Predicted performance and actual performance are subsequently evaluated to adjust parameters and create the best model fit. However, due to the difficulty of quantifying “performance” in football this type of analysis has yet to be investigated.

This thesis has gone some way to explaining the reliability and sensitivity of a range fatigue and physical performance measures. A key statistic, as discussed in the practical applications, is the MDC. This gives practitioners a threshold which they can be confident is above the noise of the test. The next step in this analysis would be to calculate the minimum practically important change as discussed by Thorpe et al. (2017). The minimum practically important change is another important threshold to consider, alongside the MDC, as it describes not only what change is detectable, but what change will have some practical relevance. This is a difficult measure to assess in sports such as football, given the multifactorial nature to what constitutes “football performance”. Future research might look to anchor changes in fatigue response or aerobic fitness to outcomes such as injury risk, match activity profiles or technical match statistics, measures that might act as surrogate key performance indicators in football.

Finally, the association between DJ-RSI performance, vertical acceleration during sub-maximal running and players’ fatigue response has been investigated throughout this thesis. Based on previous research a possible link between these assessments and lower extremity stiffness has been made (Butler *et al.*, 2003, Lloyd *et al.*, 2009). This highlight the need to assess the link between lower extremity stiffness and fatigue, potentially through jumping and hopping tasks or via tri-axial accelerometer data. Preliminary work in this area has looked promising (Buchheit *et al.*, 2015b, Buchheit *et al.*, 2018), however, recent concerns about the validity and reliability of trunk housed tri-axial accelerometers to determine peak vertical acceleration have been published (Edwards *et al.*, 2018). Future research should look to advance this area by using advanced analytical techniques, such as machine learning, to correctly quantify lower extremity stiffness from commonly worn tri-axial accelerometers and inertial measurement units (Cust *et al.*, 2018).

CHAPTER 9

9.0 Appendices

Appendix A: Example Informed Consent Form

INFORMED CONSENT FORM

Project Title: The reliability of a fatigue and recovery response in elite youth football players

Principal Investigator: John Fitzpatrick

Participant Number: ______

For the participant:

	please tick where applicable
I have read and understood the Participant Information Sheet.	☐
I have had an opportunity to ask questions and discuss this study and I have received satisfactory answers.	☐
I understand I am free to withdraw from the study at any time, without having to give a reason for withdrawing, and without prejudice.	☐
I agree to take part in this study.	☐

For the parent or guardian:

	please tick where applicable
I have read and understood the Participant Information Sheet.	☐
I agree that my child/children may participate in the research	☐

Signature of researcher... Date.....………………..   (NAME IN BLOCK LETTERS)...………………
Signature of participant... Date.....………………..   (NAME IN BLOCK LETTERS)...………………
Signature of parent or guardian................................ Date.....………………..   (NAME IN BLOCK LETTERS)..………………….

Appendix B: 5-Item Subjective Wellness Questionnaire

	1	2	3	4	5
Fatigue	Very tired	More tired than normal	Normal	Fresh	Very Fresh
Sleep Quality	Insomnia	Restless Sleep	Difficulty falling asleep	Good	Very Restful
Muscle Soreness	Very Sore	Increase in soreness/ tightness	Normal	Feeling Good	Feeling Great
Stress Level	Highly Stressed	Feeling Stressed	Normal	Relaxed	Very Relaxed
Mood	Highly annoyed/irritable	Aggravated/short tempered	Less interested than usual	A generally good mood	Very positive mood

Appendix C: 3-Item Subjective Wellness Questionnaire

Subjective Wellness Questionnaire

1. How do you rate your Fatigue today?

1 Very Bad	2	3	4	5	6	7	8	9	10 Very Good

2. How do you rate your Sleep last Night

1 Very Bad	2	3	4	5	6	7	8	9	10 Very Good

3. How do you rate your Muscle Soreness today?

1 Very Bad	2	3	4	5	6	7	8	9	10 Very Good

Appendix D: Example Standardised Training Session

Physical Training Report

Tuesday 09 May 2017

Day: 313 Week: 45

Session Load Score:	81.8 High	Players RPE:	8.9 Very Hard
Aim of Session:		Main Session Outcome:	HSD 112%

Training Group: - CD, FB, CM, AM, WM, FW

Full Session

Session Time	90	mins
Work Time	75	mins

Drill	MINS
Testing	15
Passing Drills	8
6v3 Possession	16
9v7 Possession	20
Crossing and Finishing	10
8 x 15:15 MAS Runs	6

	absolute	per min	relative
TD	8629	95.9	80%
HSD	524	5.8	112%
SPR	85	0.9	46%
A/D Load	403	4.5	89%
Max Vel	29.8		103%
m > MAS	1635	18.2	
t > MAS	04:58	0.0	

Drill 1

Testing — Warm Up; 2 x 40 m Sprint; 1500m MAS Test

	absolute	per min	relative
TD	2376	158.4	142%
HSD	49	3.3	67%
SPR	7	0.5	23%
A/D	61	4.1	86%
t > MAS	02:11	00:09	0%

Drill 2

Passing Drills — Area: 20 x 20; Time: 4 x 2 min

	absolute	per min	relative
TD	605	75.6	68%
HSD	2	0.3	5%
SPR	1	0.1	5%
A/D	21	2.6	56%
t > MAS	00:01	00:00	0%

Drill 3

6v3 Possession — Area: 20 x 30; Time: 4 x 4 min

	absolute	per min	relative
TD	1709	106.8	95%
HSD	90	5.6	115%
SPR	29	1.8	92%
A/D	130	8.1	172%
t > MAS	00:37	00:02	0%

Drill 4

9v7 Possession — Area: 70 x 55; Time: 2 x 10 min

	absolute	per min	relative
TD	2385	119.2	107%
HSD	38	1.9	39%
SPR	11	0.6	29%
A/D	119	6.0	127%
t > MAS	00:29	00:01	0%

Drill 5

Crossing and Finishing — Area: 57 x 74; Time: 2 x 5 min

	absolute	per min	relative
TD	834	83.4	74%
HSD	4	0.4	8%
SPR	2	0.2	10%
A/D	34	3.4	73%
t > MAS	00:03	00:00	0%

Drill 6

8 x 15:15 MAS Runs — Area: Individualised distance; Time: 8 x 15:15

	absolute	per min	relative
TD	721	120.2	107%
HSD	341	56.9	1163%
SPR	36	6.0	310%
A/D	33	5.5	117%
t > MAS	01:36	00:16	0%

Velocity Profile

Appendix E: Multicollinearity matrix for training load variable in Chapter 6-Part I

	TD (m)	**AD Load** (m)	**m>HSR** (m)	**t>HSR** (min)	**m>VHSR** (m)	**t>VHSR** (min)	**m>MAS** (m)	**t>MAS** (min)	**m>30ASR** (m)	**t>30ASR** (min)	**HRE** (AU)	**sRPE** (AU)
TD (m)	-											
AD Load (m)	0.62	-										
m>HSR (m)	0.76	0.71	-									
t>HSR (min)	0.78	0.71	0.95	-								
m>VHSR (m)	0.66	0.66	0.94	0.91	-							
t>VHSR (min)	0.67	0.66	0.95	0.92	0.94	-						
m>MAS (m)	0.72	0.62	0.97	0.98	0.89	0.90	-					
t>MAS (min)	0.70	0.60	0.96	0.97	0.86	0.87	0.92	-				
m>30ASR (m)	0.59	0.38	0.81	0.79	0.83	0.82	0.82	0.80	-			
t>30ASR (min)	0.59	0.37	0.80	0.79	0.81	0.80	0.82	0.80	0.96	-		
HRE (AU)	0.15	0.23	0.35	0.34	0.36	0.36	0.33	0.31	0.32	0.33	-	
sRPE (AU)	0.46	0.24	0.68	0.68	0.66	0.66	0.72	0.72	0.78	0.79	0.29	-

Abbreviations: TD; total distance, AD Load; acceleration and deceleration distance >2m.s^{-2}, m>HSR; high speed running distance > 17 km.h^{-1}, t>HSR; high speed running time > 17 km.h^{-1}, m>VHSR; very high speed running distance > 21 km.h^{-1}, t>VHSR; very high speed running time > 21 km.h^{-1}, m>MAS; distance > MAS km.h^{-1}, t>MAS; time > MAS km.h^{-1}, m>30ASR; distance > 30% ASR km.h^{-1}, t>30ASR; time > 30% ASR km.h^{-1}, HRE; heart rate exertion, sRPE; session rating of perceived exertion.

11.0 References

Abbott, W., Brickley, G. and Smeeton, N. J. (2018a) An individual approach to monitoring locomotive training load in English Premier League academy soccer players. *International Journal of Sports Science & Coaching*,1747954118771181.

Abbott, W., Brickley, G. and Smeeton, N. J. (2018b) Physical demands of playing position within English Premier League academy soccer. *Journal of Human Sport and Exercise,* 13(2),285-295.

Abt, G. and Lovell, R. (2009) The use of individualized speed and intensity thresholds for determining the distance run at high-intensity in professional soccer. *J. Sports Sci.,* 27(9),893-898.

Ade, J. D., Harley, J. A. and Bradley, P. S. (2014) Physiological response, time–motion characteristics, and reproducibility of various speed-endurance drills in elite youth soccer players: Small-sided games versus generic running. *Int. J. Sports Physiol. Perform.,* 9(3),471-479.

Aguiar, M., Botelho, G., Lago, C., Maças, V. and Sampaio, J. (2012) A review on the effects of soccer small-sided games. *Journal of human kinetics,* 33,103-113.

Akenhead, R., French, D., Thompson, K. and Hayes, P. (2015) The physiological consequences of acceleration during shuttle running. *Int. J. Sports Med.,* 36(04),302-307.

Akenhead, R., French, D., Thompson, K. G. and Hayes, P. R. (2014) The acceleration dependent validity and reliability of 10 Hz GPS. *J. Sci. Med. Sport,* 17(5),562-566.

Akenhead, R., Harley, J. A. and Tweddle, S. P. (2016) Examining the external training load of an English Premier League football team with special reference to acceleration. *J. Strength Cond. Res.,* 30(9),2424-2432.

Akenhead, R., Hayes, P. R., Thompson, K. G. and French, D. (2013) Diminutions of acceleration and deceleration output during professional football match play. *J. Sci. Med. Sport,* 16(6),556-561.

Akenhead, R., Marques, J. B. and Paul, D. J. (2017) Accelerometer load: a new way to measure fatigue during repeated sprint training? *Science and Medicine in Football,* 1(2),151-156.

Akenhead, R. and Nassis, G. P. (2016) Training load and player monitoring in high-level football: current practice and perceptions. *Int. J. Sports Physiol. Perform.,* 11(5),587-593.

Akubat, I. (2014) 'Training Load Monitoring in Soccer', in Van Winckel, J. (ed.) *Fitness in soccer : the science and practical application*. Klein-Gelmen: Moveo Ergo Sum, pp. 167-184.

Akubat, I., Patel, E., Barrett, S. and Abt, G. (2012) Methods of monitoring the training and match load and their relationship to changes in fitness in professional youth soccer players. *J. Sports Sci.,* 30(14),1473-1480.

Ali, A. and Farrally, M. (1991) Recording soccer players' heart rates during matches. *J. Sports Sci.,* 9(2),183-189.

Allen, D. G. and Trajanovska, S. (2012) The multiple roles of phosphate in muscle fatigue. *Front. Physiol.,* 3,463.

Andersen, P. and Henriksson, J. (1977) Training induced changes in the subgroups of human type II skeletal muscle fibres. *Acta Physiol. Scand.,* 99(1),123-125.

Andersson, H. M., Raastad, T., Nilsson, J., Paulsen, G., Garthe, I. and Kadi, F. (2008) Neuromuscular fatigue and recovery in elite female soccer: effects of active recovery. *Med. Sci. Sports Exerc.,* 40(2),372-380.

Arampatzis, A., Schade, F., Walsh, M. and Brüggemann, G.-P. (2001) Influence of leg stiffness and its effect on myodynamic jumping performance. *J. Electromyogr. Kinesiol.,* 11(5),355-364.

Ascensão, A., Rebelo, A., Oliveira, E., Marques, F., Pereira, L. and Magalhães, J. (2008) Biochemical impact of a soccer match—analysis of oxidative stress and muscle damage markers throughout recovery. *Clin. Biochem.,* 41(10-11),841-851.

Atkinson, G. (2003) Does size matter for sports performance researchers? *J. Sports Sci.,* 21(2),73-74.

Atkinson, G. and Nevill, A. M. (1998) Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Med.,* 26(4),217-238.

Aughey, R. J. (2011) Applications of GPS technologies to field sports. *Int. J. Sports Physiol. Perform.,* 6(3),295-310.

Bangsbo, J. (1994) Energy demands in competitive soccer. *J. Sports Sci.,* 12,5-12.

Bangsbo, J., Graham, T., Kiens, B. and Saltin, B. (1992) Elevated muscle glycogen and anaerobic energy production during exhaustive exercise in man. *The Journal of Physiology,* 451(1),205-227.

Bangsbo, J., Iaia, F. M. and Krustrup, P. (2007) Metabolic response and fatigue in soccer. *Int. J. Sports Physiol. Perform.,* 2(2),111-127.

Bangsbo, J., Johansen, L., Graham, T. and Saltin, B. (1993) Lactate and H+ effluxes from human skeletal muscles during intense, dynamic exercise. *The Journal of Physiology,* 462(1),115-133.

Bangsbo, J., Madsen, K., Kiens, B. and Richter, E. (1996) Effect of muscle acidity on muscle metabolism and fatigue during intense exercise in man. *The Journal of physiology,* 495(2),587-596.

Bangsbo, J., Mohr, M. and Krustrup, P. (2006) Physical and metabolic demands of training and match-play in the elite football player. *J. Sports Sci.,* 24(07),665-674.

Bangsbo, J., Nørregaard, L. and Thorsoe, F. (1991) Activity profile of competition soccer. *Can. J. Sport Sci.,* 16(2),110-116.

Banister, E. and Calvert, T. (1980) Planning for future performance: implications for long term training. *Can. J. Appl. Sport Sci.,* 5(3),170-176.

Banister, E., Calvert, T., Savage, M. and Bach, T. (1975) A systems model of training for athletic performance. *Australian Journal of Sports Medicine,* 7(3),57-61.

Banister, E. W. (1991) 'Modeling Elite Athletic Performance', in MacDougall, J.D., Wenger, H.A. & Green, H.J. (eds.) *Physiological Testing of Elite Athletes*. Champaign, Illinois: Human Kinetics, pp. 403-424.

Barnes, C., Archer, D., Bush, M., Hogg, R. and Bradley, P. (2014) The evolution of physical and technical performance parameters in the English Premier League. *Int. J. Sports Med.,* 35,1-6.

Barrett, S., McLaren, S., Spears, I., Ward, P. and Weston, M. (2018) The Influence of Playing Position and Contextual Factors on Soccer Players' Match Differential Ratings of Perceived Exertion: A Preliminary Investigation. *Sports,* 6(1),13.

Barrett, S., Midgley, A. and Lovell, R. (2014) PlayerLoad™: Reliability, convergent validity, and influence of unit position during treadmill running. *Int. J. Sports Physiol. Perform.,* 9(6),945-952.

Barrett, S., Midgley, A., Reeves, M., Joel, T., Franklin, E., Heyworth, R., Garrett, A. and Lovell, R. (2016) The within-match patterns of locomotor efficiency during professional soccer match play: Implications for injury risk? *J. Sci. Med. Sport,* 19(10),810-815.

Barry, B. K. and Enoka, R. M. (2007) The neurobiology of muscle fatigue: 15 years later. *Integr. Comp. Biol.,* 47(4),465-473.

Batterham, A. M. and Atkinson, G. (2005) How big does my sample need to be? A primer on the murky world of sample size estimation. *Phys. Ther. Sport,* 6(3),153-163.

Batterham, A. M. and Hopkins, W. G. (2006) Making meaningful inferences about magnitudes. *Int. J. Sports Physiol. Perform.,* 1(1),50-57.

Beattie, K. and Flanagan, E. P. (2015) Establishing the reliability & meaningful change of the drop-jump reactive strength index. *J Aust Strength Cond,* 23(5),12-18.

Bellenger, C. R., Fuller, J. T., Nelson, M. J., Hartland, M., Buckley, J. D. and Debenedictis, T. A. (2015) Predicting maximal aerobic speed through set distance time-trials. *Eur. J. Appl. Physiol.,* 115(12),2593-2598.

Bigland-Ritchie, B. and Woods, J. (1984) Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle & Nerve: Official Journal of the American Association of Electrodiagnostic Medicine,* 7(9),691-699.

Billat, L. V. (2001) Interval training for performance: a scientific and empirical practice. *Sports Med.,* 31(1),13-31.

Billat, L. V. and Koralsztein, J. P. (1996) Significance of the Velocity at V̇o2max and Time to Exhaustion at this Velocity. *Sports Med.*, 22(2),90-108.

Billat, V., Demarle, A., Paiva, M. and Koralsztein, J. (2002) Effect of training on the physiological factors of performance in elite marathon runners (males and females). *Int. J. Sports Med.,* 23(05),336-341.

Billat, V. L., Flechet, B., Petit, B., Muriaux, G. and Koralsztein, J.-p. (1999) Interval training at VO2max: effects on aerobic performance and overtraining markers. *Med. Sci. Sports Exerc.,* 31(1),156-163.

Billat, V. L., Slawinski, J., Bocquet, V., Demarle, A., Lafitte, L., Chassaing, P. and Koralsztein, J.-P. (2000) Intermittent runs at the velocity associated with maximal oxygen uptake enables subjects to remain at maximal oxygen uptake for a longer time than intense but submaximal runs. *Eur. J. Appl. Physiol.,* 81(3),188-196.

Bland, J. M. and Altman, D. G. (1997) Statistics notes: Cronbach's alpha. *Br. Med. J.,* 314,572.

Bloomfield, J., Polman, R. and O'Donoghue, P. (2007) Physical demands of different positions in FA Premier League soccer. *J. Sports Sci. Med.,* 6(1),63.

Borg, E. and Kaijser, L. (2006) A comparison between three rating scales for perceived exertion and two different work tests. *Scand. J. Med. Sci. Sports,* 16(1),57-69.

Borg, G., Hassmén, P. and Lagerström, M. (1987) Perceived exertion related to heart rate and blood lactate during arm and leg exercise. *Eur. J. Appl. Physiol. Occup. Physiol.,* 56(6),679-685.

Borresen, J. and Lambert, M. I. (2007) Changes in heart rate recovery in response to acute changes in training load. *Eur. J. Appl. Physiol.*, 101(4),503-511.

Bowen, L., Gross, A. S., Gimpel, M. and Li, F.-X. (2017) Accumulated workloads and the acute: chronic workload ratio relate to injury risk in elite youth football players. *Br. J. Sports Med.,* 51(5),452-459.

Boyd, L. J., Ball, K. and Aughey, R. J. (2011) The reliability of MinimaxX accelerometers for measuring physical activity in Australian football. *Int. J. Sports Physiol. Perform.,* 6(3),311-321.

Bradley, P. S., Di Mascio, M., Peart, D., Olsen, P. and Sheldon, B. (2010) High-intensity activity profiles of elite soccer players at different performance levels. *The journal of strength & conditioning research*, 24(9),2343-2351.

Bradley, P. S., Sheldon, W., Wooster, B., Olsen, P., Boanas, P. and Krustrup, P. (2009) High-intensity running in English FA Premier League soccer matches. *J. Sports Sci.,* 27(2),159-168.

Bravo, D. F., Impellizzeri, F. M., Rampinini, E., Castagna, C., Bishop, D. and Wisloff, U. (2008) Sprint vs. interval training in football. *Int. J. Sports Med.,* 29(08),668-674.

Brownstein, C. G., Dent, J. P., Parker, P., Hicks, K. M., Howatson, G., Goodall, S. and Thomas, K. (2017) Etiology and recovery of neuromuscular fatigue following competitive soccer match-play. *Front. Physiol.,* 8,831.

Buchheit, M. (2014) Monitoring training status with HR measures: do all roads lead to Rome? *Front. Physiol.,* 5,73.

Buchheit, M., Gray, A. and Morin, J.-B. (2015a) Assessing stride variables and vertical stiffness with GPS-embedded accelerometers: preliminary insights for the monitoring of neuromuscular fatigue on the field. *Journal of Sports Science and Medicine*, 14(4),698.

Buchheit, M., Gray, A. and Morin, J. (2015b) Assessing stride variables and vertical stiffness with GPS-embedded accelerometers: preliminary insights for the monitoring of neuromuscular fatigue on the field. *J. Sports Sci. Med.,* 14(4),698.

Buchheit, M., Haddad, H. A., Simpson, B. M., Palazzi, D., Bourdon, P. C., Salvo, V. D. and Mendez-Villanueva, A. (2014) Monitoring accelerations with GPS in football: time to slow down? *Int. J. Sports Physiol. Perform.,* 9(3),442-445.

Buchheit, M., Lacome, M., Cholley, Y. and Simpson, B. M. (2018) Neuromuscular responses to conditioned soccer sessions assessed via GPS-embedded accelerometers: Insights into tactical periodization. *Int. J. Sports Physiol. Perform.,* 13(5),577-583.

Buchheit, M. and Laursen, P. (2013a) High-Intensity Interval Training, Solutions to the Programming Puzzle: Part I: Cardiopulmonary Emphasis. *Sports Med.,* 43(5),313–338.

Buchheit, M. and Laursen, P. (2013b) High-Intensity Interval Training, Solutions to the Programming Puzzle: Part II: Anaerobic Energy, Neuromuscular Load and Practical Applications. *Sports Med.,* 43(10),927-954.

Buchheit, M. and Mendez-Villanueva, A. (2013) Reliability and stability of anthropometric and performance measures in highly-trained young soccer players: effect of age and maturation. *J. Sports Sci.,* 31(12),1332-1343.

Buchheit, M., Mendez-Villanueva, A., Quod, M. J., Poulos, N. and Bourdon, P. (2010a) Determinants of the variability of heart rate measures during a competitive period in young soccer players. *Eur. J. Appl. Physiol.,* 109(5),869-878.

Buchheit, M., Mendez-Villanueva, A., Simpson, B. and Bourdon, P. (2010b) Repeated-sprint sequences during youth soccer matches. *Int. J. Sports Med.,* 31(10),709-716.

Buchheit, M., Racinais, S., Bilsborough, J., Bourdon, P., Voss, S., Hocking, J., Cordy, J., Mendez-Villanueva, A. and Coutts, A. (2013) Monitoring fitness, fatigue and running performance during a pre-season training camp in elite football players. *J. Sci. Med. Sport,* 16(6),550-555.

Bundle, M. W., Hoyt, R. W. and Weyand, P. G. (2003) High-speed running performance: a new approach to assessment and prediction. *J. Appl. Physiol.,* 95(5),1955-1962.

Bush, M., Barnes, C., Archer, D. T., Hogg, B. and Bradley, P. S. (2015) Evolution of match performance parameters for various playing positions in the English Premier League. *Human movement science,* 39,1-11.

Busso, T., Carasso, C. and Lacour, J.-R. (1991) Adequacy of a systems structure in the modeling of training effects on performance. *J. Appl. Physiol.,* 71(5),2044-2049.

Butler, R. J., Crowell III, H. P. and Davis, I. M. (2003) Lower extremity stiffness: implications for performance and injury. *Clinical Biomechanics,* 18(6),511-517.

Butterfield, T. A., Best, T. M. and Merrick, M. A. (2006) The dual roles of neutrophils and macrophages in inflammation: a critical balance between tissue damage and repair. *Journal of athletic training,* 41(4),457.

Byrne, C., Twist, C. and Eston, R. (2004) Neuromuscular function after exercise-induced muscle damage. *Sports Med.,* 34(1),49-69.

Carling, C., Bloomfield, J., Nelsen, L. and Reilly, T. (2008) The role of motion analysis in elite soccer. *Sports Med.,* 38(10),839-862.

Carling, C. and Dupont, G. (2011) Are declines in physical performance associated with a reduction in skill-related performance during professional soccer match-play? *J. Sports Sci.,* 29(1),63-71.

Carling, C., Gregson, W., McCall, A., Moreira, A., Wong, D. P. and Bradley, P. S. (2015) Match running performance during fixture congestion in elite soccer: research issues and future directions. *Sports Med.,* 45(5),605-613.

Carroll, T. J., Taylor, J. L. and Gandevia, S. C. (2016) Recovery of central and peripheral neuromuscular fatigue after exercise. *J. Appl. Physiol.,* 122(5),1068-1076.

Casamichana, D. and Castellano, J. (2010) Time–motion, heart rate, perceptual and motor behaviour demands in small-sides soccer games: Effects of pitch size. *J. Sports Sci.,* 28(14),1615-1623.

Charter, R. A. (1996) Revisiting the standard errors of measurement, estimate, and prediction and their application to test scores. *Percept. Mot. Skills,* 82,1139-1144.

Chen, M. J., Fan, X. and Moe, S. T. (2002) Criterion-related validity of the Borg ratings of perceived exertion scale in healthy individuals: a meta-analysis. *J. Sports Sci.,* 20(11),873-899.

Christensen, P. M., Krustrup, P., Gunnarsson, T. P., Kiilerich, K., Nybo, L. and Bangsbo, J. (2011) VO2 kinetics and performance in soccer players after intense training and inactivity. *Med. Sci. Sports Exerc.,* 43(9),1716-1724.

Colby, M. J., Dawson, B., Heasman, J., Rogalski, B. and Gabbett, T. J. (2014) Accelerometer and GPS-derived running loads and injury risk in elite Australian footballers. *The Journal of Strength & Conditioning Research,* 28(8),2244-2252.

Cormack, S. J., Mooney, M. G., Morgan, W. and McGuigan, M. R. (2013) Influence of neuromuscular fatigue on accelerometer load in elite Australian football players. *Int. J. Sports Physiol. Perform.,* 8(4),373-378.

Cormack, S. J., Newton, R. U., McGuigan, M. R. and Cormie, P. (2008a) Neuromuscular and endocrine responses of elite players during an Australian rules football season. *Int. J. Sports Physiol. Perform.,* 3(4),439-453.

Cormack, S. J., Newton, R. U., McGuigan, M. R. and Doyle, T. L. (2008b) Reliability of measures obtained during single and repeated countermovement jumps. *Int. J. Sports Physiol. Perform.,* 3(2),131-144.

Cronbach, L. J. (1951) Coefficient alpha and the internal structure of tests. *Psychometrika,* 16(3),297-334.

Cummins, C., Orr, R., O'Connor, H. and West, C. (2013) Global positioning systems (GPS) and microtechnology sensors in team sports: a systematic review. *Sports Med.,* 43(10),1025-1042.

Cust, E. E., Sweeting, A. J., Ball, K. and Robertson, S. (2018) Machine and deep learning for sport-specific movement recognition: a systematic review of model development and performance. *J. Sports Sci.,*1-33.

De Ste Croix, M., Priestley, A. M., Lloyd, R. S. and Oliver, J. (2015) ACL injury risk in elite female youth soccer: Changes in neuromuscular control of the knee following soccer-specific fatigue. *Scand. J. Med. Sci. Sports,* 25(5).

Dellal, A., Chamari, K., Pintus, A., Girard, O., Cotte, T. and Keller, D. (2008) Heart rate responses during small-sided games and short intermittent running training in elite soccer players: a comparative study. *The Journal of Strength & Conditioning Research,* 22(5),1449-1457.

Di Salvo, V., Gregson, W., Atkinson, G., Tordoff, P. and Drust, B. (2009) Analysis of high intensity activity in Premier League soccer. *Int. J. Sports Med.,* 30(03),205-212.

Drust, B. (2018) An individual approach to monitoring locomotive training load in English Premier League academy soccer players. *International Journal of Sports Science & Coaching,* 13(3),429-430.

Dupont, G., Akakpo, K. and Berthoin, S. (2004) The effect of in-season, high-intensity interval training in soccer players. *J. Strength Cond. Res.,* 18(3),584-589.

Dupont, G., McCall, A., Prieur, F., Millet, G. P. and Berthoin, S. (2010) Faster oxygen uptake kinetics during recovery is related to better repeated sprinting ability. *Eur. J. Appl. Physiol.,* 110(3),627-634.

Dupont, G., Millet, G. P., Guinhouya, C. and Berthoin, S. (2005) Relationship between oxygen uptake kinetics and performance in repeated running sprints. *Eur. J. Appl. Physiol.,* 95(1),27-34.

Edwards, A., Clark, N. and Macfadyen, A. (2003) Lactate and ventilatory thresholds reflect the training status of professional soccer players where maximum aerobic power is unchanged. *J. Sports Sci. Med.*, 2(1),23.

Edwards, R. H. (1981) Human muscle function and fatigue. *Human muscle fatigue: physiological mechanisms*,1-18.

Edwards, S. (1993) *The heart rate monitor book.* New York: Polar Electro Oy.

Edwards, S., White, S., Humphreys, S., Robergs, R. and O'Dwyer, N. (2018) Caution using data from triaxial accelerometers housed in player tracking units during running. *J. Sports Sci.*,1-9.

Ekblom, B. (1986) Applied physiology of soccer. *Sports Med.*, 3(1),50-60.

Ekblom, B., Astrand, P.-O., Saltin, B., Stenberg, J. and Wallström, B. (1968) Effect of training on circulatory response to exercise. *J. Appl. Physiol.*, 24(4),518-528.

Ekblom, B. and Hermansen, L. (1968) Cardiac output in athletes. *J. Appl. Physiol.*, 25(5),619-625.

Enoka, R. M. and Duchateau, J. (2008) Muscle fatigue: what, why and how it influences muscle function. *The Journal of physiology*, 586(1),11-23.

Esco, M. R. and Flatt, A. A. (2014) Ultra-short-term heart rate variability indexes at rest and post-exercise in athletes: evaluating the agreement with accepted recommendations. *J. Sports Sci. Med.*, 13(3),535.

Farley, C. T., Blickhan, R., Saito, J. and Taylor, C. R. (1991) Hopping frequency in humans: a test of how springs set stride frequency in bouncing gaits. *J. Appl. Physiol.*, 71(6),2127-2132.

Fatouros, I. G., Chatzinikolaou, A., Douroudos, I. I., Nikolaidis, M. G., Kyparos, A., Margonis, K., Michailidis, Y., Vantarakis, A., Taxildaris, K. and Katrabasas, I. (2010) Time-course of changes in oxidative stress and antioxidant status responses following a soccer game. *The Journal of Strength & Conditioning Research*, 24(12),3278-3286.

Filaire, E., Lac, G. and Pequignot, J.-M. (2003) Biological, hormonal, and psychological parameters in professional soccer players throughout a competitive season. *Percept. Mot. Skills*, 97(3_suppl),1061-1072.

Finch, C. F. and Marshall, S. W. 2016. Let us stop throwing out the baby with the bathwater: towards better analysis of longitudinal injury data. BMJ Publishing Group Ltd and British Association of Sport and Exercise Medicine.

Foster, C. (1998) Monitoring training in athletes with reference to overtraining syndrome. *Med. Sci. Sports Exerc.*, 30,1164-1168.

Foster, C., Daines, E., Hector, L., Snyder, A. C. and Welsh, R. (1996) Athletic performance in relation to training load. *Wis. Med. J.*, 95(6),370-374.

Gabbett, T. J. (2016) The training-injury prevention paradox: should athletes be training smarter and harder? *Br. J. Sports Med.*,bjsports-2015-095788.

Gaitanos, G. C., Williams, C., Boobis, L. H. and Brooks, S. (1993) Human muscle metabolism during intermittent maximal exercise. *J. Appl. Physiol.,* 75(2),712-719.

Gandevia, S. C. (2001) Spinal and supraspinal factors in human muscle fatigue. *Physiol. Rev.,* 81(4),1725-1789.

Gastin, P. B., Meyer, D. and Robinson, D. (2013) Perceptions of wellness to monitor adaptive responses to training and competition in elite Australian football. *The Journal of Strength & Conditioning Research*, 27(9),2518-2526.

Gathercole, R. J., Sporer, B. C., Stellingwerff, T. and Sleivert, G. G. (2015) Comparison of the capacity of different jump and sprint field tests to detect neuromuscular fatigue. *J. Strength Cond. Res.,* 29(9),2522-2531.

Gaudino, P., Iaia, F., Alberti, G., Strudwick, A., Atkinson, G. and Gregson, W. (2013) Monitoring training in elite soccer players: systematic bias between running speed and metabolic power data. *Int. J. Sports Med.,* 34(11),963-968.

Girard, O., Brocherie, F., Tomazin, K., Farooq, A. and Morin, J.-B. (2016) Changes in running mechanics over 100-m, 200-m and 400-m treadmill sprints. *J. Biomech.,* 49(9),1490-1497.

Glatthorn, J. F., Gouge, S., Nussbaumer, S., Stauffacher, S., Impellizzeri, F. M. and Maffiuletti, N. A. (2011) Validity and reliability of Optojump photoelectric cells for estimating vertical jump height. *J. Strength Cond. Res.,* 25(2),556-560.

Gregson, W., Drust, B., Atkinson, G. and Salvo, V. (2010) Match-to-match variability of high-speed activities in premier league soccer. *Int. J. Sports Med.,* 31(04),237-242.

Halson, S. L. (2014) Monitoring training load to understand fatigue in athletes. *Sports Med.,* 44(2),139-147.

Hamilton, D. (2009) Drop jumps as an indicator of neuromuscular fatigue and recovery in elite youth soccer athletes following tournament match play. *Journal of Australian Strength and Conditioning,* 17(4),3-8.

Harley, J. A., Barnes, C. A., Portas, M., Lovell, R., Barrett, S., Paul, D. and Weston, M. (2010) Motion analysis of match-play in elite U12 to U16 age-group soccer players. *J. Sports Sci.,* 28(13),1391-1397.

Hartmann, U. and Mester, J. (2000) Training and overtraining markers in selected sport events. *Med. Sci. Sports Exerc.,* 32(1),209-215.

Helgerud, J., Engen, L. C., Wisløff, U. and Hoff, J. (2001) Aerobic endurance training improves soccer performance. *Med. Sci. Sports Exerc.,* 33(11),1925-1931.

Helgerud, J., Høydal, K., Wang, E., Karlsen, T., Berg, P., Bjerkaas, M., Simonsen, T., Helgesen, C., Hjorth, N. and Bach, R. (2007) Aerobic high-intensity intervals improve V˙ O2max more than moderate training. *Med. Sci. Sports Exerc.,* 39(4),665-671.

Hemingway, H., Croft, P., Perel, P., Hayden, J. A., Abrams, K., Timmis, A., Briggs, A., Udumyan, R., Moons, K. G. and Steyerberg, E. W. (2013) Prognosis research strategy (PROGRESS) 1: a framework for researching clinical outcomes. *BMJ,* 346,e5595.

Hill-Haas, S. V., Coutts, A. J., Dawson, B. T. and Rowsell, G. J. (2010) Time-motion characteristics and physiological responses of small-sided games in elite youth players: the influence of player number and rule changes. *The journal of strength & conditioning research,* 24(8),2149-2156.

Hoff, J., Wisløff, U., Engen, L. C., Kemi, O. J. and Helgerud, J. (2002) Soccer specific aerobic endurance training. *Br. J. Sports Med.,* 36(3),218-221.

Holloszy, J. and Coyle, E. F. (1984) Adaptations of skeletal muscle to endurance exercise and their metabolic consequences. *J. Appl. Physiol.,* 56(4),831-838.

Hooper, S. L. and Mackinnon, L. T. (1995) Monitoring overtraining in athletes. *Sports Med.,* 20(5),321-327.

Hopkins, W. G. (2000) Measures of reliability in sports medicine and science. *Sports Med.,* 30(1),1-15.

Hopkins, W. G. (2015) *Spreadsheets for analysis of validity and reliability*: Sportscience. Available at: (sportsci.org/2015/ValidRely.htm).

Hopkins, W. G. (2017) *Spreadsheets for analysis of controlled trials, crossovers and time series*: Sportscience. Available at: (sportsci.org/2017/wghxls.htm).

Hopkins, W. G., Marshall, S., Batterham, A. and Hanin, J. (2009) Progressive statistics for studies in sports medicine and exercise science. *Med. Sci. Sports Exerc.,* 41(1),3.

Howatson, G. and Van Someren, K. A. (2008) The prevention and treatment of exercise-induced muscle damage. *Sports Med.,* 38(6),483-503.

Hunter, F., Bray, J., Towlson, C., Smith, M., Barrett, S., Madden, J., Abt, G. and Lovell, R. (2015) Individualisation of time-motion analysis: a method comparison and case report series. *Int. J. Sports Med.,* 36(1),41-48.

Impellizzeri, F. M. and Maffiuletti, N. A. (2007) Convergent evidence for construct validity of a 7-point likert scale of lower limb muscle soreness. *Clin. J. Sport Med.,* 17(6),494-496.

Impellizzeri, F. M., Marcora, S. M., Castagna, C., Reilly, T., Sassi, A., Iaia, F. and Rampinini, E. (2006) Physiological and performance effects of generic versus specific aerobic training in soccer players. *Int. J. Sports Med.,* 27(06),483-492.

Impellizzeri, F. M., Rampinini, E., Coutts, A. J., Sassi, A. and Marcora, S. M. (2004) Use of RPE-based training load in soccer. *Med. Sci. Sports Exerc.,* 36(6),1042-1047.

Impellizzeri, F. M., Rampinini, E. and Marcora, S. M. (2005) Physiological assessment of aerobic training in soccer. *J. Sports Sci.,* 23(6),583-592.

Ispirlidis, I., Fatouros, I. G., Jamurtas, A. Z., Nikolaidis, M. G., Michailidis, I., Douroudos, I., Margonis, K., Chatzinikolaou, A., Kalistratos, E. and Katrabasas, I. (2008) Time-course of changes in inflammatory and performance responses following a soccer game. *Clin. J. Sport Med.,* 18(5),423-431.

Jacobs, I., Westlin, N., Karlsson, J., Rasmusson, M. and Houghton, B. (1982) Muscle glycogen and diet in elite soccer players. *Eur. J. Appl. Physiol. Occup. Physiol.,* 48(3),297-302.

Jennings, D., Cormack, S., Coutts, A. J., Boyd, L. J. and Aughey, R. J. (2010) Variability of GPS units for measuring distance in team sport movements. *Int. J. Sports Physiol. Perform.,* 5(4),565-569.

Jeong, T.-S., Reilly, T., Morton, J., Bae, S.-W. and Drust, B. (2011) Quantification of the physiological loading of one week of “pre-season” and one week of “in-season” training in professional soccer players. *J. Sports Sci.,* 29(11),1161-1166.

Johnston, R. D., Gabbett, T. J., Jenkins, D. G. and Hulin, B. T. (2015) Influence of physical qualities on post-match fatigue in rugby league players. *J. Sci. Med. Sport,* 18(2),209-213.

Johnston, R. J., Watsford, M. L., Kelly, S. J., Pine, M. J. and Spurrs, R. W. (2014) Validity and interunit reliability of 10 Hz and 15 Hz GPS units for assessing athlete movement demands. *The Journal of Strength & Conditioning Research,* 28(6),1649-1655.

Jones, A. M. and Carter, H. (2000) The effect of endurance training on parameters of aerobic fitness. *Sports Med.,* 29(6),373-386.

Jones, C. M., Griffiths, P. C. and Mellalieu, S. D. (2017) Training load and fatigue marker associations with injury and illness: A systematic review of longitudinal studies. *Sports Med.,* 47(5),943-974.

Jones, R. M., Cook, C. C., Kilduff, L. P., Milanović, Z., James, N., Sporiš, G., Fiorentini, B., Fiorentini, F., Turner, A. and Vučković, G. (2013) Relationship between repeated sprint ability and aerobic capacity in professional soccer players. *The Scientific World Journal,* 2013.

Jones, S. and Drust, B. (2008) Physiological and technical demands of 4 v 4 and 8 v 8 games in elite youth soccer players. *Kinesiology: International journal of fundamental and applied kinesiology,* 39(2),150-156.

Kellmann, M. and Kallus, K. W. (2001) *Recovery-stress questionnaire for athletes: User manual.* Human Kinetics.

Kelly, D. M. and Drust, B. (2009) The effect of pitch dimensions on heart rate responses and technical demands of small-sided soccer games in elite players. *J. Sci. Med. Sport,* 12(4),475-479.

Krustrup, P., Mohr, M., Amstrup, T., Rysgaard, T., Johansen, J., Steensberg, A., Pedersen, P. K. and Bangsbo, J. (2003) The yo-yo intermittent recovery test: physiological response, reliability, and validity. *Med. Sci. Sports Exerc.*, 35(4),697-705.

Krustrup, P., Mohr, M., Steensberg, A., Bencke, J., KjÆr, M. and Bangsbo, J. (2006) Muscle and blood metabolites during a soccer game: implications for sprint performance. *Med. Sci. Sports Exerc.*, 38(6),1165-1174.

Lago-Peñas, C., Rey, E., Lago-Ballesteros, J., Casáis, L. and Domínguez, E. (2011) The influence of a congested calendar on physical performance in elite soccer. *The Journal of Strength & Conditioning Research*, 25(8),2111-2117.

Latash, M. L. and Zatsiorsky, V. M. (1993) Joint stiffness: Myth or reality? *Human Movement Science,* 12(6),653-692.

Lee, C. R. and Farley, C. T. (1998) Determinants of the center of mass trajectory in human walking and running. *J. Exp. Biol.,* 201(21),2935-2944.

Leger, L. and Boucher, R. (1980) An indirect continuous running multistage field test: the Universite de Montreal track test. *Canadian Journal of Applied Sports Science,* 5,77-84.

Lloyd, R. S., Oliver, J. L., Hughes, M. G. and Williams, C. A. (2009) Reliability and validity of field-based measures of leg stiffness and reactive strength index in youths. *J. Sports Sci.*, 27(14),1565-1573.

Lolli, L., Batterham, A. M., Hawkins, R., Kelly, D. M., Strudwick, A. J., Thorpe, R., Gregson, W. and Atkinson, G. 2017. Mathematical coupling causes spurious correlation within the conventional acute-to-chronic workload ratio calculations. BMJ Publishing Group Ltd and British Association of Sport and Exercise Medicine.

Lolli, L., Batterham, A. M., Hawkins, R., Kelly, D. M., Strudwick, A. J., Thorpe, R. T., Gregson, W. and Atkinson, G. 2018. The acute-to-chronic workload ratio: an inaccurate scaling index for an unnecessary normalisation process? : BMJ Publishing Group Ltd and British Association of Sport and Exercise Medicine.

Lorenzen, C., Williams, M. D., Turk, P. S., Meehan, D. L. and Kolsky, D. J. C. (2009) Relationship between velocity reached at VO2max and time-trial performances in elite Australian rules footballers. *Int. J. Sports Physiol. Perform.,* 4(3),408-411.

Lovell, R. and Abt, G. (2013) Individualization of time–motion analysis: a case-cohort example. *Int. J. Sports Physiol. Perform.,* 8(4),456-458.

Lucia, A., Hoyos, J., Santalla, A., Earnest, C. and Chicharro, J. L. (2003) Tour de France versus Vuelta a Espana: which is harder? *Med. Sci. Sports Exerc.,* 35(5),872-878.

Magalhães, J., Rebelo, A., Oliveira, E., Silva, J. R., Marques, F. and Ascensão, A. (2010) Impact of Loughborough Intermittent Shuttle Test versus soccer match on physiological, biochemical and neuromuscular parameters. *Eur. J. Appl. Physiol.,* 108(1),39.

Malik, M., Bigger, J. T., Camm, A. J., Kleiger, R. E., Malliani, A., Moss, A. J. and Schwartz, P. J. (1996) Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. *Eur. Heart J.,* 17(3),354-381.

Malone, J. J., Di Michele, R., Morgans, R., Burgess, D., Morton, J. P. and Drust, B. (2015a) Seasonal training-load quantification in elite English premier league soccer players. *Int. J. Sports Physiol. Perform.,* 10(4),489-497.

Malone, J. J., Lovell, R., Varley, M. C. and Coutts, A. J. (2017a) Unpacking the black box: applications and considerations for using GPS devices in sport. *Int. J. Sports Physiol. Perform.,* 12(Suppl 2),S2-18-S12-26.

Malone, J. J., Murtagh, C. F., Morgans, R., Burgess, D. J., Morton, J. P. and Drust, B. (2015b) Countermovement jump performance is not affected during an in-season training microcycle in elite youth soccer players. *The Journal of Strength & Conditioning Research,* 29(3),752-757.

Malone, S., Roe, M., Doran, D. A., Gabbett, T. J. and Collins, K. (2017b) High chronic training loads and exposure to bouts of maximal velocity running reduce injury risk in elite Gaelic football. *J. Sci. Med. Sport,* 20(3),250-254.

Manzi, V., Bovenzi, A., Impellizzeri, M. F., Carminati, I. and Castagna, C. (2013) Individual training-load and aerobic-fitness variables in premiership soccer players during the precompetitive season. *The Journal of Strength & Conditioning Research,* 27(3),631-636.

Manzi, V., Castagna, C., Padua, E., Lombardo, M., D'Ottavio, S., Massaro, M., Volterrani, M. and Iellamo, F. (2009a) Dose-response relationship of autonomic nervous system responses to individualized training impulse in marathon runners. *American Journal of Physiology-Heart and Circulatory Physiology,* 296(6),H1733-H1740.

Manzi, V., Iellamo, F., Impellizzeri, F., D'ottavio, S. and Castagna, C. (2009b) Relation between individualized training impulses and performance in distance runners. *Med. Sci. Sports Exerc.,* 41(11),2090-2096.

McCall, A., Carling, C., Nedelec, M., Davison, M., Le Gall, F., Berthoin, S. and Dupont, G. (2014) Risk factors, testing and preventative strategies for non-contact injuries in professional football: current perceptions and practices of 44 teams from various premier leagues. *Br. J. Sports Med.,* 48,1352-1357.

McClay, I. and Cavanagh, P. (1994) Relationship between foot placement and mediolateral ground reaction forces during running. *Clinical Biomechanics,* 9(2),117-123.

McLean, B. D., Coutts, A. J., Kelly, V., McGuigan, M. R. and Cormack, S. J. (2010) Neuromuscular, endocrine, and perceptual fatigue responses during different length between-match microcycles in professional rugby league players. *Int. J. Sports Physiol. Perform.,* 5(3),367-383.

McMahon, S. and Wenger, H. A. (1998) The relationship between aerobic fitness and both power output and subsequent recovery during maximal intermittent exercise. *J. Sci. Med. Sport,* 1(4),219-227.

McNair, D., Lorr, M. and Droppleman, L. (1981) Profile of mood states: EdITS manual. *San Diego, CA: Educational and Industrial Testing Service*.

Meeusen, R., Duclos, M., Foster, C., Fry, A., Gleeson, M., Nieman, D., Raglin, J., Rietjens, G., Steinacker, J. and Urhausen, A. (2013) Prevention, diagnosis, and treatment of the overtraining syndrome: joint consensus statement of the European College of Sport Science and the American College of Sports Medicine. *Med. Sci. Sports Exerc.,* 45(1),186-205.

Mendez-Villanueva, A. and Buchheit, M. (2013) Football-specific fitness testing: adding value or confirming the evidence? *J. Sports Sci.,* 31(13),1503-1508.

Mendez-Villanueva, A., Buchheit, M., Simpson, B. and Bourdon, P. (2013) Match play intensity distribution in youth soccer. *Int. J. Sports Med.,* 34(2),101-110.

Mendez-Villanueva, A., Hamer, P. and Bishop, D. (2008) Fatigue in repeated-sprint exercise is related to muscle power factors and reduced neuromuscular activity. *Eur. J. Appl. Physiol.,* 103(4),411-419.

Metzger, J. and Moss, R. (1990) Effects of tension and stiffness due to reduced pH in mammalian fast-and slow-twitch skinned skeletal muscle fibres. *The Journal of physiology,* 428(1),737-750.

Midgley, A. W., McNaughton, L. R. and Jones, A. M. (2007) Training to enhance the physiological determinants of long-distance running performance. *Sports Med.,* 37(10),857-880.

Midgley, A. W., McNaughton, L. R. and Wilkinson, M. (2006) Is there an optimal training intensity for enhancing the maximal oxygen uptake of distance runners? *Sports Med.,* 36(2),117-132.

Mikesell, K. A. and Dudley, G. A. (1984) Influence of intense endurance training on aerobic power of competitive distance runners. *Med. Sci. Sports Exerc.,* 16(4),371-375.

Mohr, M., Draganidis, D., Chatzinikolaou, A., Barbero-Álvarez, J. C., Castagna, C., Douroudos, I., Avloniti, A., Margeli, A., Papassotiriou, I. and Flouris, A. D. (2016) Muscle damage, inflammatory, immune and performance responses to three football games in 1 week in competitive male players. *Eur. J. Appl. Physiol.,* 116(1),179-193.

Mohr, M., Krustrup, P. and Bangsbo, J. (2003) Match performance of high-standard soccer players with special reference to development of fatigue. *J. Sports Sci.,* 21(7),519-528.

Mohr, M., Krustrup, P. and Bangsbo, J. (2005) Fatigue in soccer: a brief review. *J. Sports Sci.,* 23(6),593-599.

Morgans, R., Orme, P., Anderson, L., Drust, B. and Morton, J. P. (2014) An intensive winter fixture schedule induces a transient fall in salivary IgA in English Premier League soccer players. *Res. Sports Med.,* 22(4),346-354.

Morton, R., Fitz-Clarke, J. and Banister, E. (1990) Modeling human performance in running. *J. Appl. Physiol.*, 69(3),1171-1177.

Mourot, L., Bouhaddi, M., Tordi, N., Rouillon, J.-D. and Regnard, J. (2004) Short-and long-term effects of a single bout of exercise on heart rate variability: comparison between constant and interval training exercises. *Eur. J. Appl. Physiol.,* 92(4-5),508-517.

Nédélec, M., McCall, A., Carling, C., Legall, F., Berthoin, S. and Dupont, G. (2012) Recovery in soccer: Part 1 — Post-Match Fatigue and Time Course of Recovery. *Sports Med.,* 42(12),997-1015.

Nielsen, J. J., Mohr, M., Klarskov, C., Kristensen, M., Krustrup, P., Juel, C. and Bangsbo, J. (2004) Effects of high-intensity intermittent training on potassium kinetics and performance in human skeletal muscle. *The Journal of physiology,* 554(3),857-870.

Nikooyan, A. A. and Zadpoor, A. A. (2012) Effects of muscle fatigue on the ground reaction force and soft-tissue vibrations during running: a model study. *IEEE Trans. Biomed. Eng.,* 59(3),797-804.

Nordsborg, N., Mohr, M., Pedersen, L. D., Nielsen, J. J., Langberg, H. and Bangsbo, J. (2003) Muscle interstitial potassium kinetics during intense exhaustive exercise: effect of previous arm exercise. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology,* 285(1),R143-R148.

Olthof, S. B., Frencken, W. G. and Lemmink, K. A. (2018) Match-derived relative pitch area changes the physical and team tactical performance of elite soccer players in small-sided soccer games. *J. Sports Sci.,* 36(14),1557-1563.

Owen, A., Twist, C. and Ford, P. (2004) Small-sided games: the physiological and technical effect of altering pitch size and player numbers. *Insight,* 7(2),50-53.

Owen, A. L., Wong, D. P., Dunlop, G., Groussard, C., Kebsi, W., Dellal, A., Morgans, R. and Zouhal, H. (2016) High-intensity training and salivary immunoglobulin a responses in professional top-level soccer players: effect of training intensity. *J. Strength Cond. Res.,* 30(9),2460-2469.

Padulo, J., D'Ottavio, S., Pizzolato, F., Smith, L. and Annino, G. (2012) Kinematic analysis of soccer players in shuttle running. *Int. J. Sports Med.,* 33(6),459.

Patterson, M., McGrath, D. and Caulfield, B. 'Using a tri-axial accelerometer to detect technique breakdown due to fatigue in distance runners: a preliminary perspective'. *Engineering in Medicine and Biology Society, EMBC, 2011 Annual International Conference of the IEEE*: IEEE, 6511-6514.

Plews, D. J., Laursen, P. B., Kilding, A. E. and Buchheit, M. (2014) Heart-rate variability and training-intensity distribution in elite rowers. *Int. J. Sports Physiol. Perform.,* 9(6),1026-1032.

Plews, D. J., Laursen, P. B., Stanley, J., Kilding, A. E. and Buchheit, M. (2013) Training adaptation and heart rate variability in elite endurance athletes: opening the door to effective monitoring. *Sports Med.,* 43(9),773-781.

Raastad, T., Owe, S. G., Paulsen, G., Enns, D., Overgaard, K., Crameri, R., Kiil, S., Belcastro, A., Bergersen, L. H. and Hallén, J. (2010) Changes in calpain activity, muscle structure, and function after eccentric exercise.

Rampinini, E., Bosio, A., Ferraresi, I., Petruolo, A., Morelli, A. and Sassi, A. (2011) Match-related fatigue in soccer players. *Med. Sci. Sports Exerc.,* 43(11),2161-2170.

Rampinini, E., Impellizzeri, F. M., Castagna, C., Abt, G., Chamari, K., Sassi, A. and Marcora, S. M. (2007) Factors influencing physiological responses to small-sided soccer games. *J. Sports Sci.,* 25(6),659-666.

Randers, M. B., Mujika, I., Hewitt, A., Santisteban, J., Bischoff, R., Solano, R., Zubillaga, A., Peltola, E., Krustrup, P. and Mohr, M. (2010) Application of four different football match analysis systems: A comparative study. *J. Sports Sci.,* 28(2),171-182.

Reilly, T. and Thomas, V. (1979) Estimated daily energy expenditures of professional association footballers. *Ergonomics,* 22(5),541-548.

Roe, G., Darrall-Jones, J., Till, K., Phibbs, P., Read, D., Weakley, J. and Jones, B. (2016) Between-days reliability and sensitivity of common fatigue measures in rugby players. *Int. J. Sports Physiol. Perform.,* 11(5),581-586.

Rogalski, B., Dawson, B., Heasman, J. and Gabbett, T. J. (2013) Training and game loads and injury risk in elite Australian footballers. *J. Sci. Med. Sport,* 16(6),499-503.

Rowell, A. E., Aughey, R. J., Clubb, J. and Cormack, S. J. (2018) A Standardised Small Sided Game Can Be Used to Monitor Neuromuscular Fatigue in Professional A-League Football Players. *Front. Physiol.,* 9,1011.

Rushall, B. S. (1990) A tool for measuring stress tolerance in elite athletes. *J. Appl. Sport Psychol.,* 2(1),51-66.

Russell, M., Northeast, J., Atkinson, G., Shearer, D. A., Sparkes, W., Cook, C. J. and Kilduff, L. P. (2015) Between-match variability of peak power output and creatine kinase responses to soccer match-play. *The Journal of Strength & Conditioning Research,* 29(8),2079-2085.

Sahlin, K. (1992) Metabolic factors in fatigue. *Sports Med.,* 13(2),99-107.

Sahlin, K. and Henriksson, J. (1984) Buffer capacity and lactate accumulation in skeletal muscle of trained and untrained men. *Acta Physiol. Scand.,* 122(3),331-339.

Saltin, B. (1973) Metabolic fundamentals in exercise. *Med. Sci. Sports,* 5(3),137-146.

Saltin, B. and Rowell, L. B. 'Functional adaptations to physical activity and inactivity'. *Fed. Proc.,* 1506-1513.

Saw, A. E., Main, L. C. and Gastin, P. B. (2015a) Monitoring athletes through self-report: factors influencing implementation. *J. Sports Sci. Med.,* 14(1),137.

Saw, A. E., Main, L. C. and Gastin, P. B. (2015b) Monitoring the athlete training response: subjective self-reported measures trump commonly used objective measures: a systematic review. *Br. J. Sports Med.,* 50,281-291.

Scott, B. R., Lockie, R. G., Knight, T. J., Clark, A. C. and Janse de Jonge, X. A. (2013a) A comparison of methods to quantify the in-season training load of professional soccer players. *Int. J. Sports Physiol. Perform.,* 8(2),195-202.

Scott, D. and Lovell, R. (2017) Individualisation of speed thresholds does not enhance the dose-response determination in football training. *J. Sports Sci.*,1-10.

Scott, T. J., Black, C. R., Quinn, J. and Coutts, A. J. (2013b) Validity and reliability of the session-RPE method for quantifying training in Australian football: a comparison of the CR10 and CR100 scales. *The Journal of Strength & Conditioning Research,* 27(1),270-276.

Silva, J. R., Ascensão, A., Marques, F., Seabra, A., Rebelo, A. and Magalhães, J. (2013) Neuromuscular function, hormonal and redox status and muscle damage of professional soccer players after a high-level competitive match. *Eur. J. Appl. Physiol.,* 113(9),2193-2201.

Slattery, K. M., Wallace, L. K., Murphy, A. J. and Coutts, A. J. (2006) Physiological determinants of three-kilometer running performance in experienced triathletes. *J. Strength Cond. Res.,* 20(1),47.

Smith, T. P., McNaughton, L. R. and Marshall, K. J. (1999) Effects of 4-wk training using Vmax/Tmax on VO2max and performance in athletes. *Med. Sci. Sports Exerc.,* 31(6),892-896.

Soderlund, K. and Hultman, E. (1991) ATP and phosphocreatine changes in single human muscle fibers after intense electrical stimulation. *American Journal of Physiology-Endocrinology And Metabolism,* 261(6),E737-E741.

St Clair Gibson, A., Baden, D. A., Lambert, M. I., Lambert, E. V., Harley, Y. X., Hampson, D., Russell, V. A. and Noakes, T. D. (2003) The conscious perception of the sensation of fatigue. *Sports Med.,* 33(3),167-176.

Stanley, J., Peake, J. M. and Buchheit, M. (2013) Cardiac parasympathetic reactivation following exercise: implications for training prescription. *Sports Med.,* 43(12),1259-1277.

Stølen, T., Chamari, K., Castagna, C. and Wisløff, U. (2005) Physiology of soccer. *Sports Med.,* 35(6),501-536.

Suresh, K. (2011) An overview of randomization techniques: an unbiased assessment of outcome in clinical research. *J. Hum. Reprod. Sci.,* 4(1),8.

Tanaka, H., Monahan, K. D. and Seals, D. R. (2001) Age-predicted maximal heart rate revisited. *J. Am. Coll. Cardiol.,* 37(1),153-156.

Taylor, J., Macpherson, T., Spears, I. and Weston, M. (2015) The effects of repeated-sprint training on field-based fitness measures: a meta-analysis of controlled and non-controlled trials. *Sports Med.,* 45(6),881-891.

Taylor, K., Chapman, D., Cronin, J., Newton, M. J. and Gill, N. (2012a) Fatigue monitoring in high performance sport: a survey of current trends. *J Aust Strength Cond*, 20(1),12-23.

Taylor, K., Chapman, D., Cronin, J., Newton, M. J. and Gill, N. (2012b) Fatigue monitoring in high performance sport: a survey of current trends. *Journal of Australian Strength and Conditioning*, 20(1),12-23.

Taylor, R. J., Sanders, D., Myers, T., Abt, G., Taylor, C. A. and Akubat, I. (2018) The dose-response relationship between training load and aerobic fitness in academy rugby union players. *Int. J. Sports Physiol. Perform.*, 13(2),163-169.

Thomas, K., Brownstein, C. G., Dent, J., Parker, P., Goodall, S. and Howatson, G. (2018) Neuromuscular Fatigue and Recovery after Heavy Resistance, Jump, and Sprint Training. *Med. Sci. Sports Exerc.*

Thomas, K., Dent, J., Howatson, G. and Goodall, S. (2017) Etiology and recovery of neuromuscular fatigue following simulated soccer match-play. *Med. Sci. Sports Exerc.*, 49(5),955-964.

Thorlund, J. B., Aagaard, P. and Madsen, K. (2009) Rapid muscle force capacity changes after soccer match play. *Int. J. Sports Med.*, 30(04),273-278.

Thorpe, R. T., Atkinson, G., Drust, B. and Gregson, W. (2017) Monitoring fatigue status in elite team-sport athletes: implications for practice. *Int. J. Sports Physiol. Perform.*, 12(Suppl 2),S2-27-S22-34.

Thorpe, R. T., Strudwick, A. J., Buchheit, M., Atkinson, G., Drust, B. and Gregson, W. (2015) Monitoring fatigue during the in-season competitive phase in elite soccer players. *Int. J. Sports Physiol. Perform.*, 10(8),958-964.

Thorpe, R. T., Strudwick, A. J., Buchheit, M., Atkinson, G., Drust, B. and Gregson, W. (2016) Tracking morning fatigue status across in-season training weeks in elite soccer players. *Int. J. Sports Physiol. Perform.*, 11(7),947-952.

Tomlin, D. L. and Wenger, H. A. (2001) The relationship between aerobic fitness and recovery from high intensity intermittent exercise. *Sports Med.*, 31(1),1-11.

Twist, C. and Highton, J. (2013) Monitoring fatigue and recovery in rugby league players. *Int. J. Sports Physiol. Perform.*, 8(5),467-474.

Varley, M. C. and Aughey, R. J. (2013) Acceleration profiles in elite Australian soccer. *Int. J. Sports Med.*, 34(01),34-39.

Varley, M. C., Fairweather, I. H. and Aughey, R. J. (2012) Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. *J. Sports Sci.*, 30(2),121-127.

Verheul, J., Gregson, W., Lisboa, P., Vanrenterghem, J. and Robinson, M. A. (2019) Whole-body biomechanical load in running-based sports: The validity of estimating ground reaction forces from segmental accelerations. *J. Sci. Med. Sport*, 22(6),716-722.

Weaving, D., Beggs, C., Dalton-Barron, N., Jones, B. and Abt, G. (2019) Visualizing the Complexity of the Athlete-Monitoring Cycle Through Principal-Component Analysis. *Int. J. Sports Physiol. Perform.*, 14(9),1304-1310.

Weir, J. P. (2005) Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J. Strength Cond. Res.*, 19(1),231-240.

Westerblad, H., Allen, D. G. and Lannergren, J. (2002) Muscle fatigue: lactic acid or inorganic phosphate the major cause? *Physiology*, 17(1),17-21.

Weston, M. (2013) Difficulties in determining the dose-response nature of competitive soccer matches. *J Athl Enhanc*, 2(1),1-2.

Weston, M. (2018) Training load monitoring in elite English soccer: A comparison of practices and perceptions between coaches and practitioners. *Science and Medicine in Football*,1-9.

Wrigley, R., Drust, B., Stratton, G., Scott, M. and Gregson, W. (2012) Quantification of the typical weekly in-season training load in elite junior soccer players. *J. Sports Sci.*, 30(15),1573-1580.