The Effects of Training Load on Match Performance and Injury Incidence in an English Professional Soccer Club

The thesis is presented for the Degree of Master of Science (Research and Thesis) at the University of Kent

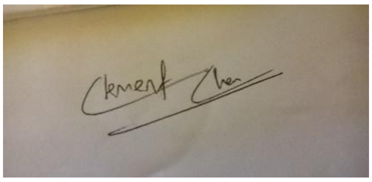
September 2019

Clement S. M. Chan

School of Sport and Exercise Science

Declaration

No part of this thesis has been submitted in support of an application for any degree or other qualification of the University of Kent, or any other University or Institution of learning.



Signed: ________________________________

Acknowledgements

Firstly, I would like to give my sincerest appreciation to my Masters supervisor, Dr James Hopker. You had kindly shared your knowledge of training load and applied sports science with me as I completed my thesis. You had provided me with guidance and advice as I struggled with the immense information and workload. Lastly, you were patient with my shortcomings and flaws as a Masters student. I will always be grateful for the opportunities you gave me in my career and hope that I have justified the faith that you have shown in me.

Special thanks to the sports science and medical department, coaches and all the staff working behind the scenes at Gillingham Football Club. They had helped me settle into working with the players and giving me invaluable guidance and showing me the ropes of working in elite football. Without them, the club would not be able to function. From the sports science and medical department, my thanks go to James Russell, Gary Hemens and Christopher Andrews. I have learnt something different from each and every one of them which has shaped me into the sports scientist I am today.

I would also like to thank Lewis Dixon, fellow intern at Gillingham Football Club. Our friendship grew as we relied and supported each other over the course of the season and beyond. I wish you all the best in your future endeavours and hope to keep in touch.

My gratitude also goes to the players of Gillingham Football Club who I have the pleasure to work with throughout the 2018/2019 season. They had made me feel welcomed to the club and I thoroughly enjoyed working with each and every one of them.

Finally, I would like to thank the people ‘off the pitch’ that have helped me get to where I am today. To my family, I would like to thank you for all the support you have given me throughout my life. Lastly, to my friends, thank you for all the support and encouragement you had given me especially during the trying times of completing this thesis.

Abstract

Training load can be divided into 2 categories: internal and external training load. External training load is the physical stress work done by the athlete. External training load can be measured by the use of global positioning system (GPS) and video-based time motion analysis. Internal training load is the physiological responses from training sessions. It can be measured by the use of heart rate monitors and rate of perceived exertion. Monitoring training load can be used to measure the players' readiness for matches and as a precautionary measure to reduce overreach from training sessions. The aim of this thesis are to quantify training periodisation practices employed by a professional football club throughout a competitive season, determine the changes to microcycle training plan according to the number of matches in a week and the neuromuscular response during weekly microcycles of different football training and match loads among professional football players and to evaluate the eccentric hamstring strength and injury occurrence in relation to training load data throughout the competitive season.

Study 1 aimed to quantify training periodisation practices employed by a professional football club throughout a competitive season. Initially, 20 players agreed to take part in the study, although only 12 players provided sufficient data to be included within the study. Training data was recorded via GPS across the competitive season, sub-divided into 4 different stages (each sub-divided into two 5-week blocks; early and late stage). Countermovement jump height was recorded for all players in order to assess their level of neuromuscular fatigue. Significant differences were observed in total distance covered ($p = 0.045$, effect size = 0.385) and high-speed distance covered ($p = 0.001$, effect size = 0.264) across the different stages of the season. There were no significant changes were observed in the training load as measured by the accumulated New Body Load ($p = 0.085$). A sub-analysis was conducted to explore the impact of fixture congestion on player training load by comparing weeks with 1 match, vs weeks with 2 matches. Significant differences were observed in total distance covered (1 match = 14076.16 ± 1569.24 m vs. 2 matches = 7874.35 ± 1923.01 m; $t(3) = 3.571$, $p = 0.038$, 95% Confidence Interval of Difference [674.40 m to 11729.23 m], effect size = 3.53), high-speed distance covered (1 match = 781.49 ± 109.89 m vs. 2 matches = 413.99 ± 91.87 m; $t(3) = 4.445$, $p = 0.021$, 95% Confidence Interval of Difference [104.39 m to 630.60 m], effect size = 3.63) and accumulated New Body Load (1 match = 281.82 ± 35.36 AU vs 2 matches = 135.93 ± 12.02 AU; $t(3) = 11.78$, $p = 0.001$, 95% Confidence Interval of Difference [106.47 AU to 185.31 AU], effect size = 5.52) for training sessions in weeks that players were preparing for 1 match vs 2 matches. No correlation was found between the total distance covered ($r = -0.001$; $p = 0.995$), high-speed distance covered ($r = 0.07$; $p = 0.547$) and New Body Load ($r = 0.101$; $p = 0.386$) with countermovement jump height. It was concluded that there was a lack of manipulation in training sessions throughout the season. However, there were efforts to reduce the training load on weeks with 2 matches. Hence, alteration in training microcycles is important for players to be optimally prepared and recuperated for the following match.

Study 2 aimed to evaluate the eccentric hamstring strength and injury occurrence in relation to training load data throughout the competitive season. Players were divided between those who had suffered hamstring injuries ($n = 6$) and those that did not during the season ($n = 14$) over the course of the season. They were required to perform isometric Nordic hamstring curl every week after a training session. No statistical differences were observed between the Nordic break-point angles (hamstring strength) of the two groups ($p = 0.299$). No significant changes were observed in the acute: chronic workload ratios between the two groups prior to injuries of the injured group ($p = 0.316$). It was concluded that eccentric hamstring strength and the acute: chronic workload ratios cannot be used to predict non-contact injury incidences.

To conclude, the present results suggest that a lack of manipulation to training load may not reduce match running performances. However, coaches and sports scientists still manipulate and periodise training for optimal preparation for matches, especially in weeks with more matches.

The use of eccentric hamstring strength tests alone and acute: chronic workload may not be suitable to predict non-contact injuries among the players.

Table of Contents

Contents

Contents

List of Figures

List of Tables

List of Abbreviations

a_f	Earth's gravity
ANOVA	Analysis of variance
ANS	Autonomic nervous system
ATP	Adenosine triphosphate
CNS	Central nervous System
ECG	Electrocardiogram
FA	Football Association
GPS	Global positioning system
HRV	Heart rate variability
J kg^{-1} m^{-1}	energy cost of accelerated running on grass
LF/HF	low to high frequency oscillations ratio
MSNA	Muscle sympathetic nerve activity
P_{met}	Metabolic power
TMA	Time-motion analysis
The IFAB	The International Football Association Board
v	running speed

CHAPTER 1: Introduction

1.1. Professional Soccer

Soccer is an intermittent sport that involves physical, technical and tactical parameters contributing to team performance (Stolen et al., 2005). From an endurance point of view, each player performs approximately 1000 to 1400 short activities, changing every 4 to 6 seconds (Mohr et al., 2003; Bangsbo et al., 1991; Reilly, 1976; Rienzi et al., 2000). Players were also required to have high levels of muscular strength and power as they are key elements to movements such as turning, sprinting and changing pace (Bangsbo, 1994). High levels of strength in upper body and lower body may also reduce injury risks in soccer (Arnason et al., 2004).

Soccer Outfield Positions	Common Match Activities
Defenders	Sprints, tackles, jumps, changing pace and direction
Midfielders	Sprints, tackles, jumps, changing pace and direction, turning
Strikers	Sprints, jumps, changing pace and direction, turning

Table 1. Soccer outfield positions and their common match activities (Ekblom, 1986; Withers, 1982; Bangsbo et al., 1991; Reilly, 1976; Rienzi et al., 2000; Helgerud et al., 2001; Mayhew and Wenger, 1985).

1.2. Fixture Congestion

In elite soccer, players should be able to play up to 50 competitive matches a season and participate in a match as regularly as 4 days over a five-match period (Strudwick, 2012). The high number of fixtures for the team often stem from their participation in domestic league and cup, and if playing at the highest level, continental cup competitions. The common period for high fixture congestion is during the Christmas period where teams have to play on Boxing day and around the New Year’s period (Kendall, 2008). During these periods of high fixture congestion, players may not get the recommended 72 hours of recovery period (Ispirlidis et al., 2008). From a performance perspective, players who played more matches over a fixed period were found to underperform than those who played less (Ekstrand et al., 2004). Moreover, the rate of injuries during matches were found to increase during periods of high fixture congestion (Dellal et al., 2013). The need to minimise injury incidence in the team becomes increasingly important. Teams with low rates of injury were found to perform better in domestic leagues as well as European cups (Hagglund et al., 2013). Few studies have investigated the effects of congested playing schedules on player performance and/or fatigue (Nassis and Gabbett, 2016).

Elite soccer had developed and much research had been conducted regarding match performance and training. Planning and execution of training sessions in preparation for matches had taken a more scientific approach (Bangsbo, 2014). New technology has allowed for changes in match performance to be studied in high time resolution (Bangsbo, 2014). Besides, the individual physical demands the individual players were exposed to in games and training became the attention of coaches and sports scientists when assessing their readiness as well as their specific tactical roles for upcoming matches (Bangsbo, 2014).

1.3. Training Periodisation

The weekly training programme for soccer players vary because of the different stages of the annual plan, number of fixtures during the season and experience of the manager or coach (Impellizzeri, et al., 2006). Training during pre-season focuses on rebuilding the fitness levels of the players who had returned following the off-season. During in-season, the aim shifts to maintaining their fitness and specific capacities developed during pre-season (Reilly, 2006). Professional players typically train 4 to 6 times per week during the competitive season (Bangsbo et al., 2006). However, they may train twice a day, 5 days per week during pre-season (Impellizzeri et al., 2006). These high-volume training sessions would dramatically increase the training demands placed on the players and result in physical and physiological changes (Goto et al., 2007).

1.4. Monitoring Training Load

The introduction of training load monitoring into sports allows coaches and sports scientists to observe and monitor quantitatively the efforts athletes put into training and matches. Training load can be defined as a holistic measure of the physical stress the athlete experiences. Training load is categorised into 2 separate branches: internal and external. Internal training load can be described as the biochemical (physical and physiological) and biomechanical stress response to exercise (Imperlizzerri et al., 2005). External training load is the physical work done by the athlete during exercise (Vanrenterghem et al., 2017). Monitoring training loads have gained importance as it provides sport scientists and coaches with valuable information regarding prescribed training programmes.

Internal training loads are commonly monitored via heart rate monitors and obtaining the player's rate of perceived exertion. A feature of the modern heart rate monitor is its ability to measure heart rate variability of an athlete. Heart rate monitors had developed even further to have larger memory capacity, allowing for more data to be stored. These data would then be downloaded for analysis of their internal training load during training or competition (Achten and Jeukendrup, 2003). Besides that, the players could rate the day's training session or match based on a category ratio scale (Borg et al., 1987). The players' rate of perceived exertion was shown to provide an alternative valid and time effective method to quantify training load from training sessions (Impellizzeri et al., 2004). External training load is often monitored via the use of global positioning systems (GPS) and video-based time motion analysis. The parameters often analysed with external training load are total distance covered, high-speed distance covered, sprint frequency, acceleration and deceleration of the players.

The match activities of the players were monitored via video-based time motion analysis or global positioning system microtechnology attached to the players. The typical total distance covered by a player during a match is 10 – 13 km (Bangsbo et al., 2006; Bangsbo et al., 1991; Mohr et al., 2003). Midfielders were found to cover the most distances compared to the other outfield positions. However, most of the distance covered were by walking or low intensity running, which required a low energy turnover (Bangsbo, 2014). High-intensity movements are important as they allow the team to create opportunities to score (Bangsbo et al., 2006). Therefore, the total amount of high intensity activity periods separates the elite players from those of lower standards, as elite international players performed approximately 28% more high intensity running (2.43 vs 1.43 km) and 58% more sprinting (650 vs 410 m) than professional players playing at a lower standard (Mohr et al., 2003).

The individual differences in physical demands among players are partly due to their varying positions in the team. Central defenders tend to cover less overall distance and perform less high intensity running than players in other positions, which is probably linked to their tactical roles and lower physical capacity (Mohr et al., 2003). Full-backs were found to cover more distance in high intensity and sprinting, while performing less headers and tackles than players in other positions. Attacking players covered distance at high intensity almost equivalent to full-backs and midfield players, but sprinted the most compared to the others (Mohr et al., 2003). They had a more marked decline in sprinting distance than midfielders and defenders (Mohr et al., 2003).

With the emergence of GPS to monitor and measure the training load of the players in training and matches, sports scientists and coaches would be able to periodise training sessions for players to be optimally prepared for matches and lowering the risk of injury. Hence, the aims of the first study in the current thesis are to quantify training periodisation practices employed by a professional soccer club throughout a competitive season and to determine the changes to microcycle training plan according to the number of matches in a week.

1.5. Injury in Soccer

Soccer has a relatively high injury rate compared to many sports (Lewin, 1989). The risk of injuries in soccer sometimes stem from the high match frequencies and year-long training (Gabbett, 2016). Previous research had shown that there is an association between training load and injury risk, whereby higher training loads increases the likelihood of injury (Malone et al., 2016). In England, a player playing professionally suffers, on average, 1.3 injuries per season and misses an average of 24 days of training and competition per injury (Hawkins et al., 2001). Studies from tournament play reported varying injury rates, from 0.5 per 1000 hours exposure to 29.9 per 1000 hours exposure (Schmidt-Olsen et al., 1985).

Division	Number of injuries	%	Position	Number of injuries	%	Age Distribution (years)	Number of injuries	%
Premier	618	26	Goalkeeper	223	9	17-22	970	41
1st Division	712	30	Defender	817	34	23-28	817	34
2nd Division	550	23	Midfielder	739	31	29-34	508	21
3rd Division	496	21	Forward	597	25	35+	81	3
Total*	2376	100		2376	99		2376	99

*Percentage totals may be subject to rounding errors associated with individual components.

Table 2. Division, playing position, and age distribution of players playing in England and their injury rates from July 1997 to end of May 1999 (Hawkins et al., 2001).

To ensure the health and safety of professional soccer players, various measures were made to prevent and control injuries. Data for the injury surveillance system were collected and the factors that influenced the occurrence of injury were identified.

Hamstring injuries are the most common injury in professional soccer (Ekstrand et al., 2011). Hamstring injuries often occur from running (Woods et al., 2004). This is because the hamstrings are active throughout the gait cycle and peak during the terminal swing and early stance phases (Chumanov et al., 2011). The hamstrings are eccentrically contracted while in maximal length to decelerate the extending knee and flexing hip (Yu et al., 2008). The eccentric hamstring strength of the players is a factor in the occurrence of hamstring strain injuries (Aagaard et al., 1998). Hence, the aim of the second study in the current thesis is to evaluate the eccentric hamstring strength and injury occurrence in relation to training load data throughout the competitive season.

1.6. Aims and Objectives

The overall purpose of the present thesis is to investigate the relationship between training load, match performance, fatigue and non-contact injuries. This will be investigated through the fulfilment of the following thesis aims:

1. The quantification of training load experienced by players within a professional soccer club throughout a competitive season.
2. To determine the changes to training load according to the number of matches in a week.
3. To determine the neuromuscular response during weekly microcycles of different soccer training and match loads among professional soccer players.
4. To evaluate the eccentric hamstring strength and injury occurrence in relation to training load data throughout the competitive season.

The successful completion of the above aims will enable a deeper understanding of the relationship between training load monitoring and match performance. This will be accomplished by the following:

1. Quantification of training periodisation practices employed by an elite soccer team will be determined through analysis of external training load data using applied methods of data collection throughout a competitive season.
2. The quantification of the daily training load of weeks with 1 match and weeks with 2 matches.
3. The neuromuscular response to a weekly microcycle of soccer training will be evaluated through the use of vertical jump assessment in professional soccer players.
4. Quantification of eccentric hamstring strength via Nordic eccentric hamstring curls and comparing the data with hamstring injury occurrence.

CHAPTER 2: Literature Review

2.1. Physiological Demands of Soccer

Soccer is an intermittent sport that requires players to have high levels of endurance, strength and power to excel in it (Stolen et al., 2005). During a match, players, on average, cover 10 to 12 km on total distance interspersed in short-term highly intensive running and sprinting activities, performing an average of 17 bursts of sprinting above 23 km/h (Di Salvo et al., 2007). However, the majority of the total distance covered were done in low-intensity running and walking. Hence, high-intensity running and sprints become more important as they are associated with more decisive periods of the match (Carling et al., 2008). A study using computerised time-motion analysis had shown that international top-class players perform 28% more high-intensity running (2.43 compared to 1.90 km) and 58% more sprinting (650 compared to 410 m) than professional players playing at a lower level (Mohr et al., 2003). These results were reflected in the top teams of a Danish League where they performed 30 – 40% more high-intensity running than teams in the middle or bottom in the league (Ingebrigsten et al., 2012). However, another study comparing the top three English soccer leagues found that the players in the Championship and League 1 (England's third-tier soccer league) performed more high-intensity running, speeds over 19 km/h, than players in the Premier League, covering average distances of 803, 881 and 681 m respectively (Bradley et al., 2013). Similarly, Championship and League 1 players covered more sprinting distance during a match (308 m and 360 m, respectively) compared to Premier League players (248 m; Bradley et al., 2013). The differences may be linked to the tactics used and playing styles in the different leagues. Interestingly, playing against opposition with higher quality might result in more high-intensity running (Di Salvo et al., 2013), possibly due to lower ball possession during the match (Lago, 2009). This is likely due to players having to cover more ground to close down their higher quality opponents and regain ball possession. These results may also indicate that higher quality players could be more selective in performing high-intensity running during matches.

Positional difference has an influence on the activity profile of a player during a match. Central defenders were found to cover the least total distance and engaged in less high-intensity running compared to those in other positions (Mohr et al., 2003). Central defenders and central defensive midfielders were found to cover the least high-speed running distance while forwards covered the most (Dellal et al., 2011). However, other studies had suggested that external midfield players cover the most high-intensity running distance (Carling et al., 2008).

Other physical demands in soccer include short accelerations, turns, actions with the ball, tackles and jumps. However, these actions are not included in high-intensity running data as the interpretation of these movements may differ between coaches and sports scientists. Another factor they are not recorded as data is because these actions were not counted as high-intensity running in the first place. For example, most maximal accelerations do not result in the player reaching the high-intensity running speed but these accelerations were still metabolically taxing on the player (Osgnach et al., 2010). These actions may also be influenced by the players' playing style. The number of tackles and jumps depends on a player's playing style and their position in the team as results vary from 3 to 27 and 1 to 36 for tackles and jumps respectively (Mohr et al., 2003).

2.2. Training Principles and Periodisation

The development of sporting performance is heavily influenced by systematic training. Training to improve sporting performance is a process that involves progressive manipulation of physical training load (Manzi et al., 2010). The professional soccer player's competitive performance is highly dependent on the complex construct where physical fitness, tactical, technical, mental aspects and injury resistance are blended (Bompa and Buzzichelli, 2009). Hence, the application of training methodology has to be specific to the sport and individual athletes for the athlete to successfully acquire these attributes. Progression in sports science research has allowed for evaluation and development of traditional training methodologies (Issurin, 2010).

Periodisation is a theoretical model that provides a framework to plan and systematically vary a player's training prescription or programme (Brown and Greenwood, 2005). Variation in the prescribed training programme is important as sustained exposure to the same training fails to elicit further adaptations (Morgans et al., 2014a). Constantly having high loading during training will risk players from fatigue and injury as well (Morgans et al., 2014a). As competition demands of both individual and team sports typically cover the yearly cycles, coaches and sport scientists have to plan an 'annual plan' for the players to give optimal performances throughout the competitive season (Bompa and Buzzichelli, 2018). The training periodisation refers to division of the entire annual plan into smaller periods and training units (Matveyev, 1981). A number of microcycles make a mesocycle, although there is no fixed number on it. Mesocycles typically vary in length, ranging from 2 weeks to several months in an annual cycle (Bompa, 2009). An example of a mesocycle is the pre-season phase. It would be made up of several microcycles to form a periodised training programme lasting 6 to 8 weeks with the aim to improve the players' fitness (Castagna et al., 2013).

2.2.1. Principles of Training Adaptation

The physiological demands of soccer are complex. This complexity arises partly from the intermittent nature of the game. The intermittent exercise associated with soccer is fuelled by aerobic and anaerobic energy systems (Morgans et al., 2014a). Therefore, activities and exercises that stress these energy systems have to be included in the training programmes of soccer players. Exercises that improve the physical components of fitness of the players, for example strength and flexibility, must be included in their training programmes to ensure they maintain their physical fitness and lower their risk of injury throughout the competitive season. Besides, technical skills such as shooting, passing and dribbling also have to be integrated into the players' weekly training programmes.

The adaptations from training are key to the development of a player. The supercompensation phenomenon is based on the interaction between load and recovery during and after exercise.

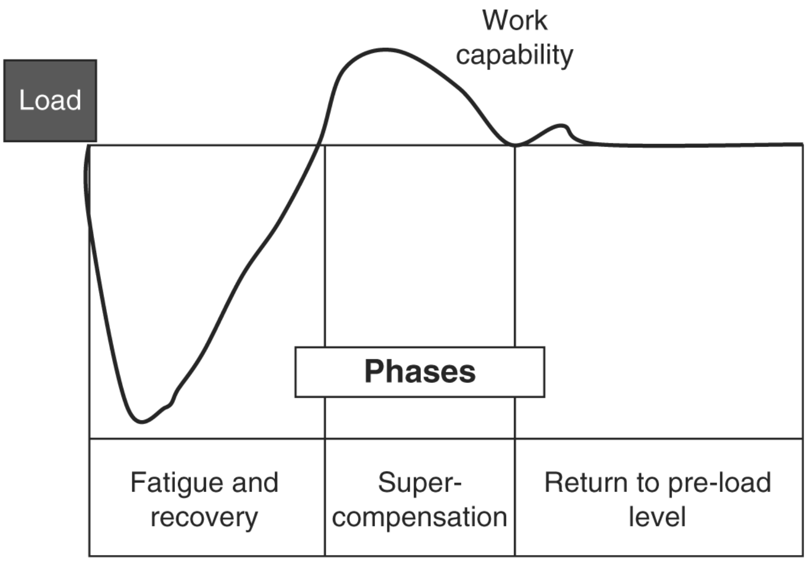


Figure 1. The supercompensation cycle, showing the trend work capability following a single load (Issurin, 2010).

The supercompensation cycle induced by physical work load on the athlete, serving as a stimulus for further reaction. The single load causes fatigue and acute reduction in the player's work capability. This phase occurs approximately 1 to 2 hours after completing an exercise bout and causes exercise-induced fatigue. This fatigue can occur in both the central and peripheral systems, which includes the central nervous and musculoskeletal systems (Davis, 1995). The second phase, after 24 to 48 hours of post exercise, the player is hit by fatigue and undergoes recovery. Towards the end of this phase, the player is able to increase his or her work capability and reach pre-load levels. Electromyographic (EMG) activity and maximal voluntary contraction tests on players going through this phase of supercompensation have found muscle function to fully restored to baseline levels (Zainuddin et al., 2006). In the third phase, which occurs 36 to 72 hours after exercise, the work capability continues to increase beyond the previous level and reaches its peak, which corresponds to the supercompensation phase. A previous study on MVC had found a secondary rebound occurring during this phase, resulting in an increase in performance capability (Nicol et al., 2006). Physiological work capability then returns to the pre-load level in the fourth phase. This phase occurs 3 to 7 days post exercise. The player has to apply another stimulus to maintain the physiological adaptations acquired from the exercise bout. If another stimulus was not applied during this period, a process termed 'involution' occurs where the physiological benefits from the supercompensation phase decrease. However, if the player is exposed to too much high training stimuli without sufficient recovery time, the ability to adapt to the training stimuli will be significantly compromised and overreaching may occur (Fry et al., 2006). Hence, it is important that the time-course of the physiological response to the stimulus is understood for effective planning of training programmes to reap the optimum training adaptations.

Training programmes for soccer players have to be multidimensional to cater for the development of energy systems and other components of fitness (Morgans et al., 2014a). Training sessions focused on development/practice of technical skills and tactical requirements must be included in annual training plans as well (Morgans et al., 2014a). These sessions frequently take priority over the course of the season, hence, limiting the amount of physical training during the season (Morgans et al., 2014a). Therefore, the need to plan training sessions becomes increasingly important to maximise the performance improvements of the players during matches.

2.2.2. Principles of Training Periodisation

A major component in training is progressive overload (Pearson et al., 2000). The principle of progressive overload suggests placing more stress on the exercising musculature than its normal (Baechle and Earle, 2000). This is necessary for training adaptations to occur. However, it is not possible to continually train because of the need for adequate recovery (Davis, 1995). Hence, periodisation is used so that athletes can train and be prepared optimally for competition (Issurin, 2010).

One of the principles of periodisation applicable in soccer is the principle of 'unity of general and specialised preparation'. (Issurin, 2010). This principle emphasises on the importance of specific workloads over a long period of early season training and maintaining general conditions over a period of frequent competitions (Issurin, 2010). A typical soccer season would be split into pre-season, in-season and off-season (Reilly, 2006). The pre-season phase is a preparatory phase for the players where training load would be high as players establish the physical, technical and psychological bases from which tactical development can occur (Bompa, 2009). With the high volume of training during this phase, the training load from pre-season is typically higher than that during in-season (Jeong et al, 2011). The high training load allows physiological adaptations to occur so the players are able to tolerate the high demands from training and matches during the in-season phase. During the in-season phase, the main goals of this phase are to dissipate fatigue and elevate preparedness, maintaining sport-specific fitness and development of technical and tactical knowledge (Bompa, 2009). Finally, the off-season phase allows players to recover physiologically and psychologically after long periods of competition. Players during this phase do minimal training before starting off with light training as they transition into the pre-season phase. Consequently, they limit the effects of detraining going into the preparatory phase of the next season (Reilly, 2006). In professional European soccer, pre-season typically lasts for 6 weeks, the in-season phase lasts for approximately 40 weeks and the off-season phase lasts for 6 weeks.

In soccer, the application of periodisation strategies is influenced by the external factors that are beyond the control of coaches and sports scientists, examples include fixture scheduling and extreme weather. Given that multiple matches would be played in a week, players may only participate in 2 to 3 training sessions in that cycle, with emphasis on recuperation (Bangsbo et al., 2006). In a typical week where 1 match is played, coaches have more opportunities to periodise training to maintain or improve physiological adaptations.

A study was conducted to investigate the effects of congested fixture period on the physical performance, technical activity and injury rate during matches (Dellal et al., 2015). The movements of the players in this study were tracked with a computerised player tracking system at a sampling rate of 25.0 Hz. The physical performance of the players were measured in distances run in four categories of running intensities: 0.0 – 12.0 km/h (walking and light-intensity running, Light-IR); 12.1 – 18.0 km/h (low intensity running, Low-IR); 18.1 – 21.0 km/h (moderate intensity running, MIR) and >21.0 km/h (high intensity running, HIR). Technical performance indicators for this study were percentage of successful passes, frequency of balls lost, total number of touches per possession and percentage of duels won. Injury was defined as the time loss injuries in which players were not capable of participating fully in training and matches because of physical complaints (Fuller et al., 2006). The results showed that physical and technical performances were not affected during the congested fixture periods (Dellal et al., 2015). The total injury occurrence during the congested fixture period was similar to those reported outside these periods. However, the rate of injury and the mean lay-off duration fluctuated during the periods of congested fixtures (Dellal et al., 2015).

These results reflect similarly on a study comparing the physical performance of players involved in a match against players involved in two matches a week in a European club participating in the Champions League across two seasons (Dupont et al., 2010). Physical performance indicators for this study were the total distance covered, high intensity distance (distance covered between 19.0 – 24.0 km/h), sprint distance (distance covered over 24.0 km/h) and the number of sprints for the 2 teams (Dupont et al., 2010). The physical performance of the players was not significantly affected by the number of matches played per week. The injury rates however were significantly higher for the group involved in two matches the week compared to those playing one match per week (Dupont et al., 2010). The high injury rate for players playing two matches per week shows that loads on the players have to be managed more carefully during training. The results of the two studies imply that playing loads of professional soccer players have the potential to deteriorate players' performance and health. Hence, a balance between the training, competition and recovery is important to maximise players' performance.

A further approach that could be applied in soccer is the 'wave-shape design of training workloads' as a short term (weekly) planning design. This approach emphasises the need to alternate days of high and low workloads, sequencing large, medium and small workloads (Issurin, 2010). The biochemical and physiological outcomes from previous studies had supported the physiological understanding behind this principle (Issurin, 2010). Post-exercise recuperation is as important as training itself as lower workloads following a training session with a high workload reduces the risk of fatigue accumulation. Coaches structure their weekly training blocks, termed microcycles, based on this principle. A microcycle has to be flexible in terms of individual session content to accommodate the individual player's working capacity, need for recovery and competition plan (Stone et al., 2007). A modification to a microcycle will consequently cause the subsequent training session to be altered as well to maintain the focus of the particular microcycle, which is for training objectives to be met (Verkhoshansky, 1985). In top level professional soccer, players will be required to play a competitive match every 3 to 4 days. During this time, the weekly microcycle will be modified to ensure the players are well prepared as well as recovered sufficiently to perform optimally (Impellizzeri et al., 2005). Training volume and intensity have to be reduced to accommodate for the congestion of fixtures (Impellizzeri et al., 2005).

There are now various models of training periodisation for both individual and team sports. The ‘three-peak preparation model’ has become the latest commonly recognised modification of traditional periodisation (Issurin, 2010). It was derived from a one-peak annual plan which was later developed into a two-peak annual plan before settling on the three-peak preparation model. The changes made on this periodisation plan was due to the progress in sport facilities, emergence of multiple competitions and the professionalism of training (Issurin, 2010).

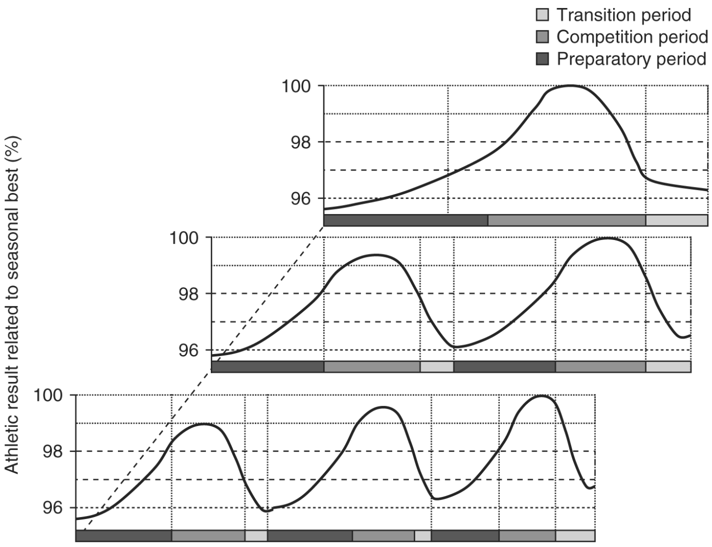


Figure 2. One-peak, two-peak and three-peak annual cycles. The annual trend of athletic results in relation to the seasonal best achievement (Issurin, 2010).

There were some limitations to the application of the traditional periodisation model. A major issue with this model was the lack of energy supply in athletes to constantly perform and train with diversified workloads (Coffey and Hawley, 2007). Next, athletes do not get sufficient recovery as different physiological systems have varying periods of recuperation (Bangsbo et al., 1991). Furthermore, athletes struggle to direct their mental concentration on multiple targets simultaneously, as demanded in sporting performance (Lidor et al., 2007). Lastly, athletes were unable to reach their peak multiple times and perform successfully during the entire annual cycle as intended by the model (Issurin, 2008).

2.2.3. Models of Training Periodisation

The non-linear periodisation model was postulated given the limitations of the traditional model. This model emphasises on the variation of the intensity of the weekly and daily training sessions. This model also uses repetition maximum zones to prescribe exercise intensity (Buford et al., 2007). The non-linear periodisation model was suggested to be more conducive in strength development as it provides frequent changes in stimuli and periods of recovery with its varying training intensity and volume (Buford et al., 2007). However, a review comparing linear and non-linear periodisation models had found no differences in strength development (Harries et al., 2015). The resistance training programmes evaluated in the review were mainly short-term interventions, making it difficult to draw conclusions on long-term effects (Harries et al., 2015).

Block periodisation was another approach to periodise training. The taxonomy of block periodisation is composed of 3 mesocycle blocks: accumulation, transmutation and realisation (Shantarovich et al., 2006). The accumulation block is for the development of basic abilities such as general aerobic endurance and strength. The transmutation block focuses on more specific abilities such as combined aerobic-anaerobic or aerobic endurance, specialised muscle endurance and proper sport-specific techniques. Lastly, the realisation phase is designed as a pre-competitive training phase and focuses on competition readiness. In terms of duration of each mesocycle, the accumulation phase typically lasts the longest, followed by the transmutation phase and lastly the realisation phase. Block periodisation had been implemented in various sports and had been widely successful in producing athletic achievements (Pyne and Tourestski, 1993).

Block periodisation is favoured among coaches and athletes, in both team and individual sports, because it pertains to the possibility of reducing total training volumes (Shantarovich et al., 2006). It provides for better monitoring of training that focuses on targeted abilities (Issurin and Kaverin, 1985). Lastly, it aids in maintaining mental concentration and motivation levels while directing the training programmes to a reduced number of targets (Lidor et al., 2007).

2.3. Training Load Monitoring

Soccer training has aspects of physical training and can be described in terms of its process (the nature of the exercise) or its outcome (anatomical, physiological, biochemical and functional adaptations) (Impellizzeri et al., 2005 and Impellizzeri et al., 2004). This aspect of training is referred to as external training load (Morgans et al., 2014a). The physiological stress from the training is referred to internal training load (Garrett and Kirkendall, 2000). The introduction of training load monitoring into sports allows coaches and sports scientists to observe and monitor quantitatively the efforts athletes put into training and matches. The advancement of technology has made it possible to quantify both internal and external training loads in soccer (Borresen and Lambert, 2009). External training load can be monitored using global positioning systems (GPS), which provides an understanding of the individual training load of the players by collecting detailed data, such as distance covered and average speed (Cummins et al., 2013). Internal training load measures include heart rates to assess the cardiovascular stress, where data is collected via heart rate monitors (Achten and Jeukendrup, 2003). The data collected by monitoring training sessions can be used to enhance training contents and subsequently improve performance during matches. Effective analysis and feedback to coaches and players are essential for the improvements to occur (Morgans et al., 2014a).

2.3.1. External Training Load

External training load is the physical work prescribed in the training plan and is determined by the organisation, quality and quantity of exercise (Coutts et al., 2017). The measures of external training load are specific to the nature of the training (Impellizzeri et al., 2019). The external training load in team sports can be typically described as total distance covered (or within specific speed thresholds), accelerations or metabolic power (Osgnach et al., 2010). Coaches prescribe training according to external training load for the desired psychophysiological responses in the players (Impellizzeri et al., 2019).

2.3.2. Global Positioning System

GPS is a satellite-based technology for navigational purposes originally devised for military use (Cummins et al., 2013). GPS technology requires a receiver to be worn by each player. The receiver draws on signals from at least four satellites orbiting the Earth to determine positional information and calculate distances, movement speeds, pathways and even altitude (Larsson, 2003). GPS technology allows three-dimensional movement of an individual or group to be tracked over time in the air, land or aquatic environments. The development of portable GPS units widens its usage in a variety of settings, including sports. These units are attached onto players to track their movements practically (Hartwig et al., 2011). Later, the external load of a player can be analysed using a dedicated software (Edgecomb and Norton, 2006). Advanced development in GPS technology had allowed for biofeedback to accompany the traditional external training load monitoring. The SPI Elite® GPS is capable of monitoring heart rates and recording information regarding the frequency and intensity of impacts from tackles and collisions. This data is possible to collect because of the built-in tri-axis accelerometer which depicts three direction types (forwards, sideways and backwards). Common parameters used for analysis of external training load are the total distance and high distance covered during training sessions and matches. Hence, the current research utilises GPS to monitor the training load of the players during the training sessions and matches. With it the researcher is able to quantify the training load of the players from training sessions and how they affect their running performance in matches. The GPS also allows the researcher to determine the effects of the training sessions on changes in performances of other tests (hamstring curl and countermovement jump).

The reliability and the validity of the GPS technology have been questioned as there are limited studies on them (Jennings et al., 2010). Most studies that did assess the reliability and validity of GPS technology were only limited to technology recording distances and positional data at 1Hz, with relatively few at 5Hz (Jennings et al., 2010). The GPS technology had developed as well in terms of data collected at a frequency of 5 Hz instead of 1 Hz during matches and training. A study was done on twenty elite Australian football players to investigate the reliability and validity of a specific GPS device (MinimaxX GPS) when data is collected at different frequencies of 1 Hz and 5 Hz (Jennings et al., 2010). The players were assessed on the different movement patterns and distances common to Australian football (Jennings et al., 2010). The movements assessed were straight line running, changing of direction and a simulated team sport running circuit, where there is a combination of sprinting, walking, jogging, maximal sprints, zigzag changing of direction and a deceleration phase to a stop (Jennings et al., 2010). It was observed that the GPS substantially underestimated the criterion distance for the striding and sprinting distances, 10 m and 20 m respectively, for both 1 Hz and 5 Hz (Jennings et al., 2010). It also underestimated the criterion distance during the tight change of direction trial at all locomotion speeds (Jennings et al., 2010). The error from the criterion distance in both the tight and gradual change of direction drills were reduced because of a higher sampling rate regardless of locomotion speed (Jennings et al., 2010). From an accuracy perspective, the validity decreased as the speed of locomotion increased over a set distance (Jennings et al., 2010). Jogging, striding and sprinting over 10 m were associated with the large errors observed (Jennings et al., 2010). However, the validity improved as the distance increased for all movement speeds for both 1 Hz and 5 Hz (Jennings et al., 2010). Validity was decreased as speeds increased for both the gradual and tight change of direction tests (Jennings et al., 2010). Reliability of GPS seems to be greatest in all forms of locomotion when moving in a straight line with higher sampling rates over longer distances, at a slower velocity (Jennings et al., 2010). GPS units are also liable to errors in accuracy depending on the land configuration and the number of satellites available for connection (Carling et al., 2008). The GPS technology's inability to accurately assess movements during rapid variations of speed over short distances scrutinises its usefulness in monitoring players' training loads during matches and training sessions. However, these findings do not agree with previous findings regarding the accuracy and reliability of GPS units as they had reported a test of accuracy results of 4.8% error rate in measuring total distance covered. Besides, a test on inter-tester reliability reported a technical error of measurement of 5.5% (Edgecomb and Norton, 2006). These technical errors of measurements can be considered when interpreting the raw data. Hence, GPS microtechnology is still widely used in team sports to quantify movement of the players in both training and competition. The reliability and validity of the GPS technology to quantify movements is still acceptable to estimate longer distances, as agreed by previous research (Petersen et al., 2009). Further development to GPS technology is required for sports scientists and coaches to be confident with its suitability to quantify short, high intensity intermittent running movement patterns common in team sports.

2.3.3. Interpretation of Data

In essence, the main purpose of contemporary measurement systems is to gather data from players concerning events in a match and the players' physical efforts. The physical efforts were derived from the data collected on speed, distance and time and compiled to assess the players' training load.

2.3.3.1. Total Distance

The total distance covered by an individual player would usually be a valuable parameter to compare between teammates and players of the opposing team to ascertain relative exertion rates. However, this parameter may not be a reflection of a player's performance as there are other factors that might affect the total distance covered. These factors are often beyond the player's control and extrinsic in nature. Examples include the team formation, technical actions, tactical role and the overall playing style of the team. A study had reported that international South American players covered about 1 km less in total distance than professionals playing in the English Premier League (Rienzi et al., 2000). It was suggested that the players in the English Premier League were able to play matches at a high pace sustained longer than their South American counterparts (Rienzi et al., 2000).

Measuring total distance run may assist coaches on assessing the physical demands of the game and if current training programmes are adequate to prepare the players for matches. Players in the English Premier League were able to cover more ground during matches compared to those playing in the former First Division (before 1992), which implies the need to update fitness training programmes then (Strudwick and Reilly, 2001). This report was reflected in another study where the total distance covered data of 300 professional European midfield players showed similar results (Di Salvo et al., 2007).

The position of the player in the team plays an important role in the total distance covered during a game. From a coaching perspective, the division of the total distance run for defending and attacking plays should be looked at to determine whether players are working as much in a defensive role as they are in attacking. The tactical roles of the player would affect the results as a more tactically defensive role, such as a holding midfielder, would cover less ground than the other midfielders when the team is attacking. In a study investigating the work-to-rest ratio by positional play in rugby league, the forward players completed more work than those playing in the back positions (1:7 and 1:6 respectively; McLellan et al., 2011). In the same study, the defensive players were reported to attain higher maximal sprint speed than those playing for forward roles (McLellan et al., 2011). These findings would be attributed to the field position and individual sprint characteristics of positional groups (Waldron et al., 2011). This is because field positions tend to influence sprint performance, whereby defensive wing players have more ground to sprint into, compared to forwards who are mostly in close proximity with the opposing players (Waldron et al., 2011). Forwards are also exposed to more contact with the opposing players, reducing their chances of generating higher speeds (King et al., 2010). In hockey, midfield players were found to cover the most total distance per match (77 m) followed by defenders (52 m) and strikers (46 m) (Gabbett, 2010). Midfield players were more involved in linking up play between the defensive and offensive players as they moved the ball up and down the pitch (Gabbett, 2010).

Interestingly, it has been reported that elite Australian football players can at times fail to meet match demands in training (Boyd and Ball, 2008). This appears largely due to high intensity and high velocity activities being between 18% and 60% lower in training than in actual matches (Boyd and Ball, 2008). Similarly, the total distance covered in adolescent rugby league training was higher in matches than in training sessions (Hartwig et al., 2011). However, the activity profile of training exceeded the ones in matches among cricket players (Petersen et al., 2009).

Nevertheless, this was only true when conditioning drills alone were taken into account without including simulation and skill-based drills (Petersen et al., 2009). Hence, it is important to acknowledge that the type of drill in training affects the activity profile of the players. This is because there are differences between the players' activity profiles in open and closed drills, where open drills tend to be more physically demanding than closed drills (Petersen et al., 2009).

When comparing the total distance covered between teams or individual players, coaches and practitioners could use this parameter as a comparison between teams of varying levels in professional soccer. A comparison between top professional Italian players and elite Danish soccer players reported that the Italians covered more distance during matches (Mohr et al., 2003). The Danish players in this study were less elite compared to the Italian players to test the hypothesis of a top-class player is the most demanding (Mohr et al., 2003). Another study done on the same elite female players competing at both club and international level showed that they covered significantly higher distance when playing for their country (Andersson et al., 2007). Hence, it is important to take into account the level of competition and the importance of the match when interpreting data on analysis of match-play (Carling et al., 2008).

2.3.3.2. Different Zone Classifications

A major parameter often monitored during training sessions and matches is the distance covered through time spent in motion at different speeds. These different speeds, together with other parameters, were divided into six activity zones. The upper zones, Zones 4 to 6, provide more insightful information regarding the players' training load and exertion during training and matches. In soccer, the players move at a submaximal level of exertion (Carling et al., 2008). Elite players were found to spend most of the total game time in low intensity zones, performing motions such as walking, jogging and standing (Strudwick and Reilly, 2001). In hindsight, movements in the high intensity zones constitute about 10% of their total distance covered (Stølen et al., 2005). Research among elite female soccer players reported that national team players covered a distance of 1.53 to 1.68 km at high speed, more than 18 km/h, while running a total distance of approximately 10 km in a whole match (Andersson et al., 2010).

Low intensity movements such as jogging, walking and standing may dominate work profiles in a soccer match, but the outcome of the game is heavily influenced by the successful attempts at scoring at high speed (Kirkendall, 2007). Elite soccer players were required to run at high intensity every 60 seconds and perform an all-out sprint every 4 minutes (Strudwick and Reilly, 2001). It was reported that players in teams that win more points within the same elite league tend to perform more high-speed running and sprinting in the most intense periods of the game as well as over the whole games compared to less successful teams (Randers et al., 2007).

There is evidence that showed the average distance and duration of sprints in elite soccer is short, where sprints are rarely more than 20 m long and tend to last approximately 4 seconds (Di Salvo et al., 2007). Hence, the players' ability to accelerate may be a more important attribute than maintaining maximal speeds throughout the game. A study on rugby union players had found that forwards start their sprints mostly from standing (41%), walking (29%), jogging (29%) and striding (13%). Therefore, based on this data, practitioners and coaches could design training programmes to enhance the players' ability to perform quicker and more efficient accelerations that could ultimately impact the outcome of matches.

There is, however, no general consensus to what speed thresholds should be used across all sports. It was usually the manufacturers of the monitoring systems that derived the movement demand classifications or they were adapted from rugby union and modified (Docherty et al., 1988). There were studies that had classified sprints, often Zone 6, as running at speeds of approximately 23 km/h (Valter et al., 2006), 24 k/h (Roberts et al., 2006) and 30 km/h (Mohr et al., 2003). The lack of standardised definition of speed thresholds would hinder accurate comparison between training load data from different studies. It is also important to highlight that the GPS reliability is decreased when the player moves over 20 km/h (Gray et al., 2010). This uncertainty is likely to be stemmed from the rapid changes in velocity that are apparent in high speed movements such as high intensity running and sprinting (Jennings et al., 2010). However, the GPS reliability may deteriorate with increased movement intensity, but its validity would improve because of the increased distance the player travels (Jennings et al., 2010). Nevertheless, the latest software used to analyse training load data now are allowing practitioners to define their own speed thresholds, therefore more objective means of analysing and comparing physical efforts of players according to different intensities of movement are possible (Di Salvo et al, 2007).This fulfils the need to individualise high intensity seed thresholds as players differ in the speed at which they begin to run at high intensity (Abt and Lovell, 2009).

2.3.3.4. Limitations

However, methodological differences have affected the collection and analysis of the total distance covered by players. This is due to the lack of standardised protocols and a need for a more thorough data analysis. Besides, there is a general assumption that energy is only expended when the player travels from one position to another on the pitch, making the evaluation of physical effort less accurate. Hence, the total energy expenditure of a player could be underestimated by the system because they can make high intensity movements during play that do not necessarily change location on the pitch. These movements include vertical jumping, pressing an opponent to regain possession of the ball and high-speed shuffling. In addition, other parameters such as acceleration, deceleration, changing of direction, physical contact and distance covered while dribbling the ball all contribute to the total physical energy expenditure. As soccer is a dynamic sport, the lack of data in these aspects restrict a valid and thorough assessment of a player's energy expenditure during match play. However, some systems have made efforts to attempt to obtain these data by adding accelerometers into their devices and utilising algorithmic filtering (www.catapultsports.com, 2019).

2.3.4. Internal Training Load

Internal training load represents the psychophysiological responses that occur during training prescribed by the coach (Impellizzeri et al., 2019). Common indicators of internal training load are heart rate, blood lactate concentration and player's perception of exertion. Internal training load is recommended as a primary measure of monitoring players as it determines the training outcome (Impellizzeri et al., 2019). The internal training load experienced from a specific external training load may vary between players, depending on specific contextual factors (Impellizzeri et al., 2019). A study that modified such factors (health, training status, nutrition, psychological status) observed that individual athletes experienced different internal training loads and adaptive processes when provided with the same external load (Vellers et al. 2018). The internal training load may also be influenced by other stressors (eg. hot conditions during training) that may affect the psychophysiological response to exercise (Impellizzeri et al., 2019).

Session ratings of perceived exertion (RPE) has also been reported to be a valid measure of internal load, but its validity was not as high as initially thought (Chen et al., 2002). The most relevant evidence of the validity of RPE scales are criterion related (Chen et al., 2002). Criterion-related validity is defined as the empirical relationship between RPE and physiological measures that reflect more directly exercise intensity (Chen et al., 2002). However, the physiological variables may be influenced by potential psychological variables (Borg, 1998), exercise history (Parfitt et al., 1996) and physiological condition (Russell, 1997). Athletes may also abuse the session rate of perceived exertion by providing false ratings to influence subsequent training sessions (Bourdon et al., 2017). It was also found that heart rates respond relatively slowly to abrupt changes in work rate and it may not accurately reflect changes in maximal oxygen uptake for the exercise (Achten and Jeukendrup, 2003). As soccer is an intermittent sport with high-intensity work during matches, heart-rate based methods of measuring internal load may not be valid (Reilly, 1997 and Impellizzeri et al., 2005). Besides, there was also the imitation of heart rate transmitter belts being disallowed during official competitive matches (Impellizzeri et al., 2005).

2.4. Neuromuscular Fatigue

As players train and play in competitive matches every week, they are bound to experience fatigue. Muscular fatigue is the decrease in maximal voluntary force or power of the muscle or muscle group induced from exercise (Bigland-Ritchie et al., 1983). Muscular fatigue is also associated with the increase in perceived effort to exert the desired force from a muscle or muscle group (Enoka and Stuart, 1992). However, many neurophysiological mechanisms are affected before the body experiences the effects of fatigue and these changes sometimes constitute advance warning of fatigue. Furthermore, the initial state of the neuromuscular system (i.e. energy reserves, ion concentrations and arrangement of contractile proteins) will be altered at the beginning of the exercise (Boyas and Guevel, 2011). Then, fatigue develops progressively until the muscle is no longer capable of performing the task. Fatigue is a multifactorial phenomenon whose mechanisms are affected by the characteristics of the tasks being performed (Boyas and Guevel, 2011). These characteristics include type and duration of the exercise, speed and duration of the muscle contraction (Enoka and Stuart, 1992).

The physiological processes involved in the generation of force in the muscle extend to the whole neuromuscular system. Many different factors may underlie and/or be involved in the expression of neuromuscular fatigue. Moreover, maintaining submaximal strength over a time period results from facilitatory and inhibitory influences of neuromuscular origin (Boyas and Guevel, 2011).

In soccer, the significant reductions in high-speed running have been observed towards the end of elite games among players (Andersson et al., 2008). The amount of high-speed running in the last 15 minutes of the game may have been correlated to the training status of the players (Krustrup et al., 2005). Substitutes being able to perform 25% more high-intensity runs and 63% more sprinting in the last quarter of the game compared to players who played the entire game (Mohr et al., 2003) support the notion that the reduction in match intensity was because of fatigue. It was reported that elite female players have an average reduction of 4% in sprint performance after physiological loading from soccer matches (Krustrup et al., 2010). This reduction was slightly higher than those observed among male players (Krustrup et al., 2006). It was suggested that the difference in reduction between them was because of the nature of the matches, where the sprint tests were performed after competitive matches (Krustrup et al., 2010) while tests were performed after friendly matches (Krustrup et al., 2006). Nevertheless, a study had found that muscle fatigue did not influence the relationships between yo-yo intermittent endurance running, high-intensity running speed and number of ball disposals (Mooney et al., 2011). However, muscular fatigue does alter the accelerometer load per minute produced among Australian football players (Mooney et al., 2013). It was suggested that the players may become inefficient in the production of a given load per minute (Mooney et al., 2013). For instance, they may become slower to accelerate, hence arriving late to duels or have a reduced ability to avoid an opponent (Mooney et al., 2013). Players also become less capable of producing a similar output as compared when they were not fatigued (Mooney et al., 2013). The decline in sprint and intermittent exercise performances during matches were found to be not correlated with the players' training status (Krustrup al., 2010). This was reflected in previous studies where physically fit players were able to perform more high-intensity running during matches (Krustrup et al., 2003; Krustrup et al., 2005; Mohr et al., 2003; Mohr et al., 2008; Rampini et al., 2007) and have the same aerobic loading during the game (Krustrup et al., 2005). This is an indication that players would utilise their physical capabilities during competitive matches. Players that had obtained high scores in the yo-yo intermittent endurance tests were found to have the lowest fatigue index in repeated sprint tests, hence indicating a relationship between training status and fatigue resistance (Krustrup et al., 2010).

2.4.1. Causes of Fatigue

Fatigue is caused by several different physiological phenomena (Place et al., 2010). Central fatigue designates the reduction in voluntary action of the muscle, which can be caused via a decrease in number and discharge rates of the motor units recruited at the start of the muscle force generation. Peripheral fatigue indicates a decrease in the contractile strength of the muscle fibres and alteration in the mechanisms underlying the transmission of the muscle action potentials (Gandevia, 2001).

Alterations in mechanisms can occur in the activation of the primary cortex of the brain, propagation of the command form the central nervous system (CNS) to the motoneurons, activation of the motor units and the muscles, neuromuscular propagation, excitation-contraction coupling, availability of the metabolic substrates, state of the intracellular medium, performance of the contractile apparatus and blood flow (Boyas and Guevel, 2011).

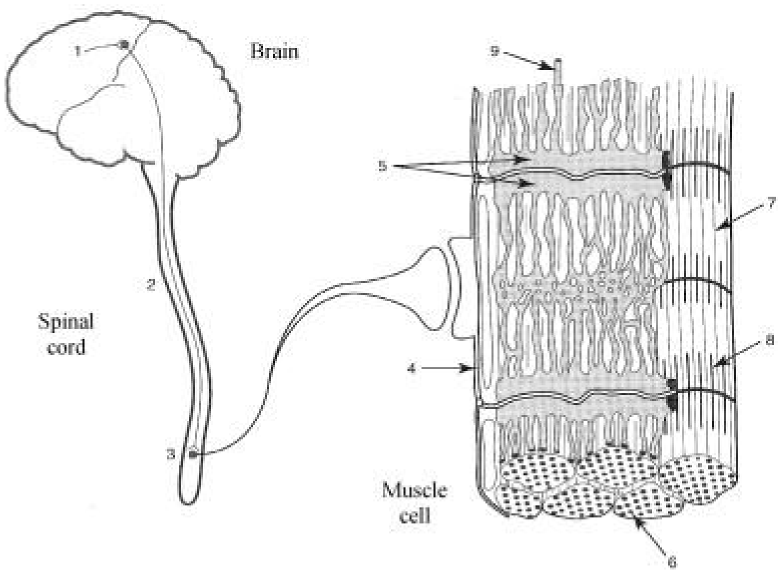


Figure 3. Sites associated with neuromuscular fatigue (Bigland-Ritchie, 1981). Fatigue may stem from alterations in: (1) activation of the primary cortex of the brain; (2) propagation of the command form the central nervous system (CNS) to the motoneurons; (3) activation of the motor units and the muscles; (4) neuromuscular propagation; (5) excitation-contraction coupling; (6) availability of the metabolic substrates; (7) state of the intracellular medium; (8) performance of the contractile apparatus; (9) blood flow.

In the context of muscular injuries from fatigue, muscles were found to be fatigued mainly from eccentric contractions (Lieber and Friden, 1988). Eccentric exercise was reported to tear the myofibrils of the muscle group, while no injury occurred in muscle groups that were concentrically and isometrically contracted (Lieber and Friden, 1988). Fatigue can cause deficiency in muscle strength, which reduces the muscle’s energy absorption capabilities, increasing the risk of injuries (Garrett, 1996). Hence, monitoring the training load of players is important to determine whether the athlete is adapting to the training programme and to minimise the risk of non-functional overreaching, injury and illness (Halson, 2014).

2.4.2. Countermovement Jump (CMJ)

The countermovement jump (CMJ) is a common test to monitor neuromuscular fatigue status in team sports (Taylor et al., 2012). CMJ performance was found to be an objective marker for neuromuscular fatigue and supercompensation (Balsalobre-Fernandez et al., 2014, Cornie et al., 2009 and Coutts et al., 2007b). However, other studies had reported varying results while using CMJ measurements (Gathercole et al., 2015, Freitas et al., 2014, Coutts et al., 2007a and Malone et al., 2015b). The variation in results could be attributed to a combination of general and specific factors. General factors may include: population type, intervention duration and the intensity of activity performed (Claudino et al., 2017).

Specific CMJ performance factors may include reporting the different kinematic and kinetic variables (e.g. jump height, peak power, relative peak power, relative power, mean power, peak velocity, eccentric time/concentric time) (Claudino et al., 2017). Some of the variables may be more sensitive than others depending on the player's neuromuscular status (McLean et al., 2010 and Mooney et al., 2013). Another factor was the use of highest and average values to assess and monitor CMJ performances (Claudino et al. 2016). Statistically, using the average value instead of the highest value had a higher probability to find the true score (Harvill, 1991 and Pereira et al., 2014). However, another research had found no significant differences between using highest [Effect Size = 0.32 (Confidence Interval 95%: 0.05-0.65)] and average [Effect Size = 0.35 (Confidence Interval 95%: 0.02-0.62)] CMJ height among soccer players (Al Haddad et al., 2015).

The CMJ test has been shown repeatedly to have high reliability (Moir et al., 2004, Arteaga et al., 2000 and Markovic et al., 2008). Previous research has found that the intraday and interday coefficient of variances (CV) of CMJ variables have a range of 1.1 to 16.2% (Gathercole et al., 2015b). A CV of < 10% as an indicative of a reliable test measure which was adopted by previous studies (Cormack et al., 2008a, Sheppard et al., 2008). The variables not within the CV < 10% were the maximum rate of force development and area under the force-velocity trace (Gathercole et al., 2015b). The authors have also suggested that the CMJ test can produce consistent results because 11 interday and 16 intraday variables tested showed CVs < 5% (Gathercole et al., 2015b). The high reliability of the CMJ test could be attributed to the use of jump height as a variable. The use of technology to assess jump height, such as jump mat, has made its computation readily accessible (Heishman et al., 2018 and Issacs, 1998). Jump height calculated with flight time was shown to have high intersession and intrasession reliabilities, supporting its use in applied practice (Heishman et al., 2020). It was suggested that the high reliability of the CMJ is partially due to the requirement to achieve a 90° knee angle during each countermovement (Theodorou and Booke, 1998). Suggesting that a standardised protocol may provide a high reliability (Cormack et al., 2008). In the case of the CMJ test, participants are required to move downward to about 90° knee flexion followed by a quick upward movement, jumping as high as possible, all in one sequence (Slinde et al., 2008).

2.5. Injury Incidence in Soccer

Soccer players are required to cope with varying degrees of asymmetrical workloads imposed on the musculoskeletal structure of the lower extremities (Fousekis et al., 2010). Consequently, this can lead to injury (Croisier et al., 2008). Approximately 25% of the lower extremity injuries in soccer are thigh muscle strains (Hawkins et al., 2001). These strains were mainly caused by a violent stretch of an eccentrically contracted muscle (hamstring strain) or an explosive contraction of a muscle (quadricep strain) (Ekstrand and Gillquist, 1983). One-third of all time-loss to injury and more than a quarter for total injury absence in elite European professional soccer clubs are because of muscle injuries among players (Ekstrand et al., 2011).

Aetiologically, risk factors for injury in soccer are influenced by both extrinsic and intrinsic factors (Warrel, 2003). Physical contact between opposing players (contact injury) constitutes the main extrinsic factor, accounting for approximately 44 - 74% of injuries (Arnason et al., 2004). Major intrinsic factors include muscular strength asymmetries, flexibility and proprioception, joint instability, anatomical and anthropometric asymmetries, age, previous injury and fatigue (Fousekis et al.,2011 and Mair et al., 1996).

Hamstring injuries are the most common in professional soccer, representing 12% of all injuries, and a team with a squad of 25 players typically suffers about 5 to 6 injuries per season (Ekstrand et al., 2011). They range in severity from minor microscopic tears (grade I) to complete ruptures (grade III) (Blankenbaker and Tuite, 2010). The most common muscle to get injured in the hamstrings is the biceps femoris (Koulouris et al., 2007). The muscle-tendon junction and adjacent muscle fibres are the typical sites of injury in the hamstrings (Askling et al., 2007).

Hamstring injuries cause the time loss from training and matches (Engebresten et al., 2010). As players miss out on training sessions, their progress in their athletic development is hindered and consequently diminishing their performance in competition (Verrall et al., 2006). English Premier League clubs were found to spend in excess £74.4 million during the 1999-2000 season because of injury to the players (Woods et al., 2002). Unfortunately, the occurrence of hamstring injuries among male professional soccer players were high and remained unchanged for more than a decade (Ekstrand et al., 2013). Hence, the amount spent on injuries among professional soccer clubs will still be high. In contrast, the maximum torques of hip extension and knee flexion occur during ground contact in sprinting (Mann, 1981).

2.5.1 Hamstring Function during Running and Potential for Strain Injury

Hamstring injury can occur from kicking, tackling, cutting and slow-speed stretching (Brooks et al., 2006). However, most hamstring injuries occur from running (Woods et al., 2004).

Hamstrings were found to be active for the entirety of a gait cycle, peaking during the terminal swing and early stance phases (Chumanov et al., 2011). During the terminal swing phase, the hamstrings are required to eccentrically contract while in maximal length to decelerate the extending knee and flexing hip (Yu et al., 2008). Among the three biarticular muscles in the hamstrings, the long head of the biceps femoris undergoes the most stretch, reaching approximately 110% in length of the muscle in upright standing during the terminal swing, followed by semitendinosus, 108.2% stretch, and semimembranosus, 107.5% stretch (Thelen et al., 2005). The hamstrings concentrically contract to extend the hip in this phase (Novacheck, 1998). However, the hamstrings were reported to eccentrically contract during the late stance phase of sprinting as well (Yu et al., 2008).

The early stance phase in the gait pattern of running was thought to pose the highest risk for the occurrence of hamstring strains (Mann, 1981). The explanation behind this was that the external joint moments were much higher in the stance phase than the swing phase as the reaction forces of the hip and knee joints were secondary to the ground force reaction (Yu et al., 2008). The high knee flexion moment, calculated from the sum of angular forces, in the late swing occurs because the hamstrings' high active and angular forces in the opposite direction are minimal. The angular forces in the opposite direction of the comes from the activity of the quadriceps and external forces. Towards the end of the swing, the vastus muscles in the quadriceps begin to activate, producing a weak contraction (Montgomery III et al., 1994). The hamstring has to work hard to reverse the inertia of the shank angular movement in the opposite direction in the late swing phase. The hamstring also works hard in the early stance phase against the potentially large opposing forces (Mann, 1981).

The occurrence of hamstring strain injury was also debated to occur in the late swing phase (Heiderscheit et al., 2005). Previous research on sprinting biomechanics showed that during the initial stance phase, the hip and knee of the sprinter go experience large flexion moments, leading to the proposition that contact loads may contribute to hamstring strains (Mann, 1981). While the hip and knee flexion moments are important factors to consider, the biomechanical state of the individual muscles from the net joint movements cannot be discerned (Pandy and Andriacchi, 2010). Recent research utilised the biomechanical simulation of sprinting and had found biarticular hamstrings to shorten throughout stance (Thelen et al. 2005). The loading on the hamstrings were also found to be consistent as the sprinter approaches near maximal speed (Chumanov et al., 2011). The biarticular hamstrings actively lengthen during the second half of the swing and peaks lengthwise prior to heel strike (Thelen et al., 2005). They also absorb kinetic energy from the swing limb during the flight phase, where neither limb is in contact with the ground (Chumanov et al., 2005). The kinetic energy absorbed in the limb is proportional to the running speed squared, so the amount of energy absorbed by the hamstrings increases with the running speed (Chumanov et al., 2005). It was argued that a previous research that had found hamstring strain to occur during the late swing phase was actually in the mid stance phase (Heiderscheit et al., 2005). The injury was reported to be during the late swing phase based on the assumption of neuromuscular delay, although the range of possible timing of the injury also included the early stance phase (Orchard, 2012).

2.5.2. Causes of Hamstring Strain Injuries

It had been argued over whether muscle strain or the magnitude of the eccentric force caused the occurrence of muscle strain injuries. Observations on *in-situ* animal models had suggested that the magnitude of muscle strain was the factor to muscle strain injuries occurring (Garrett et al., 1987, Garrett, 1990 and Mair et al., 1996). There were also studies that reported that high eccentric contractions are associated with hamstring strain injuries as the lengthening demands on the muscle exceed the mechanical limits of the tissue (Yu et al., 2008, Chumanov et al., 2007 and Lee et al., 2009). The eccentric contraction of the hamstring is a necessary condition for the occurrence of hamstring strain injuries during running (Heiderscheit et al., 2005 and Schache et al., 2009). The lack of hamstring injuries among athletes in sports biased on concentric contraction of the hamstring, such as swimming and cycling, emphasises this point (Johnson, 2003 and Mellion, 1991). There may be an inter-relationship between the muscle strain and eccentric muscle contraction that causes hamstring strain injuries.

There is also the possibility that hamstring strain injuries occur because of accumulated microscopic tears to the muscles (Morgan, 1990). Quick and long stretches on the muscle would cause damage to the single fibres that had gone through isometric and concentric contractions at the same lengths (Morgan, 1990). A theory suggested that some of the sarcomeres will lengthen nonuniformly when muscles operate on the descending limb of the length-tension curve during the eccentric contraction (Morgan, 1990). The different sarcomere lengths affect their force production capabilities, as per the properties of the length-tension curve, which indicates that there is a reduction in force production when sarcomeres extend past their optimal length (Gordan et al., 1966). Some of the sarcomeres do not return to their interdigitating pattern once the muscle is relaxed (Morgan, 1990). Repeating the lengthening process would stretch the sarcomeres and place extra tension on neighbouring myofibrils, leading the sarcomeres to tear (Morgan, 1990). As the tears accumulate, the sarcoplasmic reticulum would be damaged. Consequently, intracellular calcium would be released, contractures, clots and eventual destruction of the fibre would occur following the exercise (Morgan, 1990). This theory was not universally accepted as the expectation of the unstable sarcomere lengthening on the descending limb of the length-tension curve is flawed because the length-tension curve is determined under isometric contractions, while lengthening occurs under eccentric contractions (Butterfield, 2010). There was also evidence against longer sarcomeres would lengthen uncontrollably when required to perform eccentric contraction (Telley et al., 2006).

2.5.3. Risk Factors of Hamstring Injury

2.5.3.1 Strength Imbalances

The imbalance in strength between knee extensors and the hamstring muscle group is a prominent cause of hamstring strain injuries (Burkett, 1970). A low hamstring to quadriceps ratio suggests the hamstrings are not able to function fully in decelerating the limb movement during the terminal swing phase of running. Hence, the contraction of the quadriceps during the early swing phase of gait has the potential to produce angular momentum at the knee joint that may exceed the mechanical limits of the hamstring (Aagaard et al., 1998). Initially, research focussing on concentric strength balance between hamstrings and quadriceps, known as conventional hamstrings to quadriceps ratio, were criticised as they do not take into account the functional role of eccentric contraction of the hamstrings during the terminal swing phase of gait (Yu et al., 2008). More recent research compares the comparison of eccentric hamstring strength to concentric quadriceps strength, known as functional strength ratio (Yeung et al., 2009).

Earlier studies on the relationship between conventional hamstrings to quadriceps ratio future injury risk found that American football players with a ratio of less than 0.50 have a higher risk of hamstring injury (Burkett, 1970 and Heiser et al., 1984). However, a study on the relationship between the conventional hamstring to quadriceps or functional hamstring to quadriceps ratios to future hamstring injury incidence among Australian rules football players found no association between them (Bennell et al., 1998). The abilities and the professionalism of the participants in these studies are varied. The methodologies of these studies were also different. These factors make drawing conclusions rather difficult. A study among sprinters had found neither the conventional or the functional ratios to show significant difference between athletes suffering hamstring injuries or not (Yeung et al., 2009). The study did determine that a conventional hamstring to quadriceps ratio below 0.60 increased the injury risk in hamstrings by a 17.4-fold hazard ratio using the Cox regression analysis (Yeung et al., 2009). However, the sample size of 8 among the injured athletes should have precluded the use of this statistical method.

2.5.3.2. Flexibility

Traditionally, flexibility training was proposed as a key intervention for injury prevention among athletes despite the lack of convincing scientific evidence (Witvrouw et al., 2004). It was proposed that greater flexibility may reduce strain injury risk as the muscle-tendon unit may absorb more energy because of its greater compliance (Bennell et al., 1999).

A study on Australian football players found no relationship between hamstring flexibility and the risk of future hamstring injury incidence (Gabbe et al., 2006a). In contrast, Australian football players who previously suffered hamstring strain injuries demonstrated that greater sit-and-reach flexibility were more susceptible to suffer a recurrence of a hamstring strain injury (Gabbe et al., 2006a). It was also found in a study among soccer players that there was no increase of risk of hamstring strain injury if the player demonstrated poor hamstring flexibility, assessed via passive knee extension (Arnason et al., 2004). Other studies found a relationship between flexibility and hamstring injury (Henderson et al., 2010, Bradley and Portas, 2007 and Witvrouw et al., 2003). For example, one previous study had found that muscle tightness in the hamstring or knee flexors among the soccer players increased the likelihood of getting hamstring strain injuries (Ekstrand and Gillquist, 1982). The results were reflected in another study that suggested that players with the hamstring flexibility of less than 90° in a passive straight-leg raise were correlated significantly with hamstring strain injuries occurring in the future (Witvrouw et al., 2003).

2.5.3.3. Fatigue

Fatigue and its effects on sporting performance have often been suggested to cause injuries (Mair et al., 1996). Previous studies have shown that most hamstring strain injuries occur towards the end of the matches and training (Brooks et al., 2006 and Ekstrand et al., 2010).

Initially, the effects of fatigue were examined by comparing the muscle's ability to absorb energy while in a fatigued state against an unfatigued state (Mair et al., 1996). The muscles were put into a fatigued state via electrical stimulation (Mair et al., 1996). It was found that the fatigued muscles absorb less energy than the unfatigued muscles (Mair et al., 1996). At the same length, the fatigued and control muscle groups still fail to absorb energy, hence indicating that fatigued muscles are more susceptible to strain injuries because of the reduced capacity to resist over lengthening (Mair et al., 1996).

Fatigue in the hamstring group was found to cause an increase in the mean striding duration (Pinniger et al., 2000). The increment in the duration of the whole stride was attributed to the small but significant increase in the mean duration of the swing phase of the stride cycle (Pinniger et al., 2000). The increase in swing phase duration was suggested as the more extended thigh would place the lower limb behind the total body centre of gravity, thus needing the limb to travel a greater range of motion in preparation for the foot-ground contact stage (Pinniger et al., 2000). The greater thigh extension at toe off stage of running would cause a reduction in thigh flexion at maximum knee extension in the swing phase and athletes would not be able to move the thigh as far forward when preparing for the foot-ground contact stage in a fatigued state (Pinniger et al., 2000). Reductions in angular displacement of the lower limb, caused by the decreased activation of the muscles, was suggested to be a protective mechanism to reduce the rapid lengthening of the hamstring muscles in a fatigued state (Pinniger et al., 2000). A reduction in the hamstrings muscles' ability to generate force is thought to reduce its energy absorption capabilities, which increases the risk of musculotendinous injuries (Garrett, 1990). The increase in knee extension in running in a fatigued state was compensated by the reduction in hip flexion (Pinniger et al., 2000). These alterations in the joints of the knee and hip suggested that fatigue may cause proprioceptive alterations, a possible phenomenon reported in another knee flexor fatigue study (Allen et al., 2010). Exercise on the knee flexors led to the perception of a more flexed knee (Allen et al., 2010). This may cause runners to overextend their knees when running in a fatigued state, increasing the possibility of strain injuries in the hamstrings (Orchard, 2002).

A study of soccer-specific intermittent protocol involving 6 sets of 15-minute intermittent activity performed with a passive 15-minute halftime interval, was used to examine the effects of the soccer-specific fatigue on eccentric hamstring strength (Greig and Siegler, 2009). The authors found peak eccentric torque decreased towards the end of each half of the protocol suggesting that fatiguing effects were speed and exercise duration dependent as the absolute reduction in perk torque was greatest at the fastest testing speed (Grieg and Siegler, 2009). This reduction in peak torque towards the end of each half supports epidemiologic data proposing that hamstring strain injuries are more likely to occur at the latter stages of match play (Woods et al., 2002). The influence of speed in the occurrence of hamstring injuries indicates that explosive movements such as sprinting increases the risk of hamstring injury strain and may be crucial especially during the late-stance phase for propulsion (Clanton and Coupe, 1998).

2.5.4. Assessing Hamstring Muscle Strength

There had been a variety of methods to assess the function of the knee joint and thigh muscle function. Some of these methods include the visual inspection of the moment-joint angle curve (Grace et al., 1984), the single point peak moment (Thorstensson et al., 1976), moment at a specified knee joint angle (Perrine and Edgerton, 1978) and the hamstring-quadriceps peak moment ratio (Nosse, 1982).

Angle specific moment curves represent the moment produced throughout the range of motion of the knee (Coombs and Garbutt, 2002). The visual shape of the curve can provide a template where muscular and joint pathologies can be monitored during rehabilitation and compared to the uninjured limb (Rothstein et al., 1987).

Angle-specific moment curves were found to be useful to identify and monitor rehabilitation in pathologies such as chondromalacia patella where the peak moment ratios may be normal but reductions occurred at other joint angels (Cabri and Clarys, 1991). They were also found to identify decrements in muscle function not apparent to peak moment alone (Osternig, 1986).

However, angle specific moment curves do not take into account the function of the antagonist, hence not providing a comprehensive reciprocal muscle function (Coombs and Garbutt, 2002).

Previous attempts to screen for potential hamstring strain injury were focused on the use of isokinetics to assess the ratio of flexor (hamstring) to extensor (quadriceps) muscle strength, via concentric-flexor/concentric extensor peak-torque ratio or dynamic control ratio (eccentric knee flexor/concentric knee extensor) (Bennell et al., 1998, Orchard et al., 1997 and Aagaard et al., 1998). However, these ratios were criticised that they only take into account peak-torque values, which can occur at different angular positions in the overall range of motion and are not joint-angle specific (Sconce et al., 2015). Thus, an angle of crossover had been recommended that considers the reciprocal knee-joint muscle balance throughout the full range of motion (Graham-Smith et al., 2013). Furthermore, isokinetic testing is time-consuming and expensive (Sconce et al., 2015).

The inclusion of hamstring exercises such as Nordic hamstring curls had been shown to improve hamstring strength by 11% and dynamic-control ratios in soccer players over 10 weeks (Kujala et al., 1997). It was also reported to reduce peak-torque angle for the hamstring in athletic males and reducing the number of hamstring injury incidences in different team sports during the subsequent season (Gabbe et al., 2006, Arnason et al., 2008 and Clark et al., 2005). In theory, the greater range achieved during the Nordic hamstring curl reflects the individual's strength because gravitational moment progressively increases throughout the range of the exercise (Sconce et al., 2015). Therefore, the break point (the angle where the individual can no longer isometrically hold their trunk) could be used to assess the eccentric hamstring strength (Sconce et al., 2015).

2.5.5. Monitoring Training Load as a Preventive Measure for Injury

Monitoring the training load of athletes is important to determine whether they are adapting to the training programme and to minimise the risk of non-functional overreaching, injury and illness (Halson, 2014). Most clubs and teams implemented some form of training load monitoring as efforts to prevent injury, monitor the effectiveness of the training programme, maintain performance and prevent overtraining (Taylor et al., 2012). Self-report questionnaires appeared to be the most common practice of monitoring training load (Taylor et al., 2012). There were also teams that incorporated performance tests, which included maximal jump and /or strength tests, over-ground sprints, submaximal cycling or running tests and sport-specific tests (Taylor et al., 2012).

Monitoring training load in team sports is perceived to be more challenging than monitoring individual sport athletes because of its diverse range of activities (Halson, 2014). Such activities include resistance training, general conditioning, interval training and skill-based training. The assessment of skilled performance and 'cognitive load' cannot be ignored as it influences decision making that may affect the outcome of matches (Halson 2014). Common measures of training load in team sports are the distance covered, physiological changes and indicators of skills (Pyne and Martin, 2011). However, factors such as team tactics (including those of the opposition), environmental conditions, team cohesion and travel may influence the team's performance which will be reflected in their training load data (Halson, 2014).

It is important to monitor individual athletes in team sports as each athlete responds differently to a given training stimulus. Besides, the training load required for adaptation to occur differs significantly between athletes (Halson, 2014). Another reason to this point is that the internal load experienced by the athlete may differ from what was perceived as the coach (Wallace et al., 2009). A study had found that the athletes' and coach's perception of internal load using the session's rate of perceived exertion showed a tendency for athletes to report higher training intensities than what coaches initially designed the training session to be (Wallace et al., 2009). There were also instances where lower scores of rates of perceived exertion were reported after training sessions that were designed to have high intensity (Wallace et al., 2009). Thus, individual monitoring of the training load allows the load prescribed to tally with the intended intensities for each player.

With all the training load data gathered, clubs and teams have to incorporate this information into a database and data-management system to allow efficient access to meaningful information. A systems-based approach that integrates relevant diagnostic tests with smart sensor technology and real-time database and data management system is the future of fatigue management in elite sport (Pyne and Martin, 2011).

2.6. Acute: Chronic Workload Ratio

Research regarding workload to injury in team sports typically quantify the absolute workload to injury incidence within a team (Gabbett, 2004a, Rogalski et al., 2013 and Colby et al., 2014). However, previous research on workload-performance examined the absolute workload performed in a week, referred to as acute workload, relative to 4-week workload, known as chronic workload (Banister et al., 1975, Banister and Calvert, 1980 and Banister et al., 1986). The comparison between acute workloads and chronic workloads provides a workload index, which indicates whether an athlete's recent acute workload is greater, equal or less than the chronic workload (Hullin et al., 2016). This method of comparison is known as acute: chronic workload ratio.

The acute: chronic workload ratio had previously determined that risk of injury among fast cricket bowlers increased threefold when their acute bowling workloads doubled their chronic bowling workloads, presenting an acute: chronic workload ratio of 2 or higher (Hulin et al., 2014). It was also found that a higher chronic workload compared to the acute workload would protect athletes against injury (Hulin et al., 2014). A study on rugby league players reported that the acute: chronic workloads, derived from GPS training load data, could predict injury among the players (Hulin et al., 2016b). It was found that the greatest risk of injury was highlighted when a high chronic workload was combined with a very high acute: chronic workload ratio (Hulin et al., 2016b). Athletes displaying high chronic workload were more resistant to injury with moderately low to moderately high acute: chronic workload ratio but more susceptible to injury when exposed to large spikes in their workload, hitting acute: chronic workload ratios of approximately 1.5 (Hulin et al., 2016b).

The use of acute: chronic workload ratio provides threshold values that can be used when prescribing acute workload to obtain a high chronic workload. Acute workload can be increased to about double the workload of the chronic workload without increasing the risk of injury in the current of subsequent weeks (Hulin et al., 2016b). However, it was suggested that increasing the acute workload as an average over 2 weeks by greater than approximately 1.5 in relation to a high chronic workload or greater than 2 in relation to a low chronic workload may result in an increase in injury risk (Hulin et al., 2016b).

The performance of an athlete as they physiologically adapt to the training can be estimated between negative function ('fatigue') and a positive function ('fitness') (Banister et al., 1975). The ideal training stimulus 'sweet spot' would maximise the adaptations by having the appropriate training load while limiting the risk of injury and overtraining (Morton, 1997). Previous study on marathon and ultramarathon runners had found greater training volume and higher training intensity had improved their performance (Scrimgeour et al., 1986). In another study, 56 runners, cyclists and speed skaters participated in a 12-week training programme and exhibited an increase in performance by approximately 10% after their training load was increased 10-fold (Foster, 1998). However, previous studies had also reported that injury incidences were high when the training load was highest (Foster, 1998, Huxley et al., 2014 and Anderson et al., 2003).

2.7. Modelling the Training Load-Injury Relationship

A comparison between acute training load to the chronic training load as a ratio gives an athlete an index of preparedness (Gabbett, 2016). If the acute training load is low, indicating the athlete is experiencing minimal fatigue, and the chronic training load is high, meaning the athlete has developed fitness, the athlete is in a well-prepared state. The acute: chronic training load ratio would be around 1 or less (Gabbett, 2016). The acute: chronic training load ratio would exceed 1 if the athlete has a high acute training load and low chronic training load. The acute: chronic workload ratio shows both the positive and negative consequences of training. The ratio considers the training load of the athlete is relative to the training load he or she had prepared for (Hulin et al., 2014).

A sharp increase in the acute training load in relation to the chronic training load is often associated with the rise in risk of injury (Gabbett, 2016). The acute: chronic training load ratio within the range of 0.8 to 1.3 is considered the ideal training range to maximise response from training and minimise the risk of injury (Gabbett, 2016). Acute: chronic training load ratio of 1.5 or over is considered a 'danger zone' and the risk of injury is very high here.

Training also has a protective effect against injury. A study where rugby league players trained for more than 18 weeks before their initial injuries reduced their risk of a subsequent injury (Gabbett and Domrow, 2005). These findings were consistent in later studies where athletes with higher chronic training loads were less susceptible to injury (Hulin et al., 2014 and Hulin et al., 2016b). However, overtraining and undertraining may also increase the risk of injury (Cross et al., 2016, Lyman et al., 2001 and Dennis et al., 2003). A study on cricket bowlers found that those that bowled fewer deliveries per week with greater recovery time between sessions had a higher risk of injury, while those that bowled more deliveries with less recovery time were also at a higher risk of injury (Dennis et al., 2003). Hence, the 'U'-shaped relationship between injury and workload shows that inadequate and excessive workloads could cause injury (Gabbett, 2016).

2.8. Limitations to the Acute: Chronic Workload Ratio

There is no fixed timescale for the acute: chronic durations as they can be manipulated to fit the specificity of training or competitive patterns of soccer (Bucheit, 2017). Furthermore, the definition of injury was loosely defined in some of the studies (Hulin, 2017). There were studies that considered all types of injury, including injuries that did not result in time-loss from training and matches, while other studies only considered time-loss injuries as part of their data collection (Gabbett, 2004b, Hulin et al., 2016a and Hulin et al., 2016b). There were also limited amounts of studies taking into consideration non-contact and contact injuries (Rogalski et al., 2013 and Bowen et al., 2017).

2.9. Limitations in Training Load Monitoring

There are still some research limitations in regards to training load monitoring. The lack of general consensus as to which variables are important to look at (Akenhead and Nassis, 2016). As the amount of data increases with the emergence of different variables, coaches and sports scientists have a difficult time pinpointing the exact variables to highlight as a key variable to assess a player's performance. There is also a lack of agreement on how to analyse the longitudinal data of a diverse squad of players. Given that a squad of soccer players are made up of defenders, midfielders and strikers in general, certain variables will be more prominent in certain groups compared to the others. For example, defenders were found to cover less overall distance and perform less high-intensity running than players in other positions (Bangsbo, 1994). This would prove difficult to draw conclusions for the team and the general population of elite soccer players as a whole.

The differences in training load between players would also potentially be amplified as only 11 players of the entire squad would start a competitive match, implying that a huge group of players were not exposed to the training load from the match (Los Arcos et al., 2015). Competitive matches are the most physically demanding session of the week (Los Arcos et al., 2014). Hence, the difference between regular starters and non-starters would increase after competitive matches.

However, the overall training schedule, training session duration and physiological loading among soccer players were found to be similar across Europe during pre-season and in-season periods (Jeong et al., 2011). Player availability may also be a limitation as players are absent from training sessions during the data collection period because of injury, personal issues or called up for international duty. Transfers of players are also a limitation as players transferred out leave researchers with incomplete data set.

2.10. Limitations in Research between Training Load Monitoring and Injury Incidence

A limitation in studies researching training load monitoring and injury incidence is the lack of distinction between traumatic injuries and overuse injuries. Traumatic injuries include ankle sprains, knee sprains and thigh contusions while overuse injuries include hamstring strains quadricep strains and plantar fasciitis. The two types of injuries have to be analysed separately as differences in risk factors involved and the mechanism of injury exist between the two. Another limitation was that most studies only included injuries that led to time loss from training or matches (Gabbett and Domrow, 2007). Medical attention injuries should not be disregarded to gain a more realistic view of the medical problems in a club (Anderson et al., 2003).

2.11. Summary

In summary, this section describes the importance of training load monitoring in relation to match performance and injury prevention. The players' training load plays a key role to ensure that they are well prepared for upcoming matches, with adequate training stimulus and recovery periods. To the author's knowledge, there are limited studies on season-long training load monitoring among third-tier English soccer clubs. The practices of training load monitoring of these clubs may provide an insight on how to improve training load monitoring strategies in the future. Training load monitoring is also important to ensure that players are not fatigued as a preventive measure for non-contact injuries. The external training load would be analysed in this thesis to study their effects on the match performance and injury prevention. Besides, although eccentric hamstring strength is an intrinsic factor of hamstring injuries, there are limited studies on on-field tests for eccentric hamstring strength in relation to hamstring strain injuries. The current thesis would provide an insight on its effectiveness among professional soccer players. The hypotheses for the current thesis are:

$H1_0$: there will be no significant difference in training load metrics across the course of the competitive season.

$H1_1$: there would be a significant difference in training load metrics during the competitive season.

$H2_0$: there will be a significant difference in the training load metrics between weekly microcycles with 1 match and 2 matches.

$H2_1$: there will be no significant differences in the training load metrics between weekly microcycles with 1 match and 2 matches.

$H3_0$: there will be a correlation between the training load in a 7-day microcycle to the jump height difference.

$H3_1$: there will be no correlation between the training load in a 7-day microcycle to the jump height difference.

$H4_0$: eccentric hamstring strength of players with hamstring injuries are lower than those who did not have hamstring injuries
$H4_1$: eccentric hamstring strength of players who injured their hamstrings do not differ from those without hamstring injuries

$H5_0$: players who suffer hamstring injuries have higher acute: chronic workload ratio compared to those without hamstring injuries
$H5_1$: players who have hamstring injuries have an acute: chronic workload ratio that does not differ from those without hamstring injuries.

Chapter 3: General Methods

GPS is a satellite-based technology for navigational purposes originally devised for military use (Cummins et al., 2013). Its ability to determine positional information, calculate distances and movement speeds widens its usage into sports, especially team sports (Larsson, 2003). Common parameters used for analysis of external training load are the total distance and high distance covered during training sessions and matches.

As GPS is a more practical mode of data collection and analysis of movements, its capability to measure movement demands requires examination (Rampinini et al., 2009). Previous research has found that 10 Hz GPS units have an acceptable measure of total distance (<1% error) (Johnston et al., 2013). However, there was a difference between the actual average peak speed and the measurements of the 10 Hz GPS unit was reported to be <2.5% (Johnston et al., 2013). The inter-unit variability results of the units showed that the level of GPS error increases as the speed of movement increased for both 5 Hz and 10 Hz GPS units. The 10 Hz GPS units were reported to have a lower error level than those of the 5 Hz units (Johnston et al., 2013).

For the current study, the manufacturers of the GPS units claimed that field-based trials demonstrated that the units have a <2% error for post event data when measuring total distance travelled. The inter-unit reliability of the units also showed a <1% error when using a single threshold in speed zone distances. When measuring the accuracy and reliability of accelerations, the method reports average acceleration over 0.8 seconds, which is more accurate and reliable than to point GPS calculations due to inherited errors in GPS data. The inter-unit reliability is in the order of 5-10% difference between units (gpsports.com, 2015).

Data collection was carried out for every team training session throughout the 2018/2019 soccer season. All players had a GPS unit (GPSport, Canberra, Australia) assigned to them. Each player wore a unit in a vest supplied by the manufacturer, where the unit was securely held in place in a pouch on the upper back between the left and right scapulae. All the units were activated 30 minutes before the start of the training session or warm-up before games to allow acquisition of satellite signals as per manufacturer's instructions. After each training session or match, the units were collected and the data downloaded using the respective software package (GPSports SPI IQ Team AMS software, Canberra, Australia) on a personal computer and exported for analysis. The GPS receiver (GPSport SPI HPU Station, Canberra, Australia) and software application (GPSport SPI RealTime software, Canberra, Australia) were used to identify the exact start and end times of the training sessions and matches. The GPS units record data at 18 Hz and the accelerometer in the units record data at 100 Hz.

The variables collected for this study were the total distance covered, average total distance covered, total high-speed distance covered, average high-speed distance covered, total New Body Load and average New Body Load. High-speed distance was defined as the distance travelled at speeds of 18 km/h or higher. New body load is a variable specific to the manufacturer's GPS unit as each unit contains a tri-axis accelerometer which registers acceleration in the three planes (X, Y and Z). It is calculated from the accelerometer data and designed to reflect the volume and intensity of these accelerations. New Body Load was derived from the Magnitude of Acceleration Vector. The Magnitude Vector is normalised by subtracting a notional 1 acceleration of gravity. Then, unscaled Body Load, USBL, is calculated with the formula $USBL = NV + (NV)^3$, where NV is the normalised Magnitude of Acceleration Vector.

The data is then compiled into a spreadsheet (Microsoft Office 365, United States of America) to track the weight of training throughout the week. Data for total distance covered and NBL were readily available once the raw data was downloaded from the microunits. High-speed distance is the distance travelled by the players at more than 18 km/h. Hence, it was derived from the accumulation of the distance travelled in Zones 4, 5 and 6 from the raw data. Acute workload was derived from the accumulation of the external training load metrics over 7 days while chronic workload was derived from the average of the total workload from 28 days. The acute: chronic workload rate (ACWR) was derived from acute workload divided by the chronic workload.

CHAPTER 4: Quantification of External Training Load and the Effects on Neuromuscular Fatigue

4.1. Introduction

The advancement of technology has allowed for new measures to be developed to improve sports performance. An example of these advancements in technology is the introduction of global positioning systems (GPS) to monitor external training load. Hence, sports scientists and coaches are able to monitor the amount of work done by an athlete during training sessions and matches in real time. Consequently, they can make decisions based on the data they received that could possibly impact the outcome of the training sessions and matches.

External training load is the physical work done by an athlete during exercise (Vanrenterghem et al., 2017). Previous research has shown that GPS devices have a good level of accuracy, with approximately less than 5% of error when measuring distances (Edgecomb and Norton, 2006). It was suggested that the improvements in accuracy of more advanced GPS devices were attributed to the custom algorithms that utilises data from the 100 Hz accelerometer correcting the flaws of the 1 Hz GPS models (Coutts and Duffield, 2010). Most GPS devices have an acceptable level of reliability for most performance measures in team sports that demand short, intermittent sprinting over a non-linear course as well (Coutts and Duffield, 2010).

Internal training load can be described as the biochemical (physical and physiological) and biomechanical stress response to an exercise (Impellizzeri et al., 2005). Common markers of internal load are blood lactate concentrations, heart rates and oxygen uptake. Session rates of perceived exertion was reported to be a valid measure of internal load, but its validity was not as high as initially thought (Chen et al., 2002). The rate of perceived exertion related measures may not be as accurate among young athletes as their perception of load and effort may be unreliable (Bourdon et al., 2017). Furthermore, session rates of perceived exertion cannot be used in isolation and should be paired with other forms of training load quantification methods such as volume, jumps or pitch counts (Visnes et al., 2013 and Olsen et al., 2006). Athletes may also abuse the session rate of perceived exertion by providing false ratings to influence subsequent training sessions (Bourdon et al., 2017). It was also found that heart rates respond relatively slowly to abrupt changes in work rate and it may not accurately reflect changes in maximal oxygen uptake for the exercise (Achten and Jeukendrup, 2003). As soccer is an intermittent sport with high-intensity work during matches, heart-rate based methods of measuring internal load may not be valid (Reilly, 1997 and Impellizzeri et al., 2005). Besides, there was also the imitation of heart rate transmitter belts being disallowed during official competitive matches (Impellizzeri et al., 2005).

Part of the preparation involves training planning and structure. Training periodisation is an important element to training planning. The aim of training periodisation is to allow the athletes to reach peak training adaptations during the day or period of competition through the dissipation of fatigue and improvement of sport specific fitness (Bompa and Buzzichelli, 2018). During the implementation of a periodisation model, the annual training plan of the sport is taken into consideration. From here, long term (macrocylce) plans are established and preparatory, competitive and transition periods can be put into place. Intermediate (mesocycle) plans are later made in accordance with the number and type of competitions the team is competing in. Next is the short term (microcycle) planning to determine the workloads required for overreaching, maintenance and recovery. Microcycles in soccer are typically 3 to 7 days long, depending on the phase of the preparation and competition.

The planning of microcycles are heavily influenced by the number of competitive fixtures in a microcycle. The management of training load is typically considered in weekly microcylces with one game per week, although elite soccer players often have to play two to three times in a seven-day period (Anderson et al., 2016). In a typical one-game-week, a precompetitive unloading phase can be observed (Bosquet et al., 2007). Similarly, a study reported similar results where there was a progressive reduction of individual response to training as a competitive match approaches among young soccer players (Impellizzeri et al., 2004). The reduction of training load had been reported to improve sporting performance (Houmard, 1991 and Houmard and Johns, 1994). Commonly, training sessions with high training loads are not scheduled on days immediately before or after matches to avoid excessive strain that could hinder recovery and reduce performance (Dawson, 1996). In weeks with 2 matches per week, a similar approach was adopted as a recovery day was given after the first match and followed by 4 training days before the second match (Anderson et al., 2016). The total distances covered by the players over the course of the training days reduced after each subsequent day leading up to the match, promoting recovery among the players (Anderson et al, 2016).

As professional soccer players may have to play up to two matches per week, an accumulation of these matches over a short period may leave players experiencing residual fatigue and underperform due to insufficient recovery time as well as increase the risk of injury (Dupont et al., 2010). Research had shown that muscle soreness occurs during the post-match period, an indication of exercise-induced micro-trauma and concomitant increase in muscle damage (Nedelec et al., 2010). The damage to the muscles would result in the reduction in field-test measures of anaerobic and high-speed running performances for up to 72 hours after the match (Ascensao et al., 2008 and Rollo et al., 2014). In theory, these physiological declines should negatively affect an athlete’s performance when the recovery period between subsequent matches is short. However, several studies conducted on elite senior soccer competition had found the total distance covered by the players at various speeds were unaffected by the congested fixture period (Dupont et al., 2010, Carling and Dupont, 2011 and Djaoui et al., 2014). A study conducted on an Italian soccer team had found that their physical capacities had returned to baseline levels after 48 hours of recovery (Rampinini et al., 2011). Although a larger-scale study is required, these findings suggest that elite players are able to perform at ‘normal’ levels if consecutive matches have a 48 hour or more delay between them (Carling et al., 2015).

According to the author’s knowledge, there had been limited studies quantifying training loads of athletes in professional team sports over a season-long period. There was a study among professional soccer players that was done over 9 weeks (Los Arcos et al., 2014). There were also studies involving elite youth players where their training load was monitored for 7 weeks and also for a full-season (Impellizzeri et al., 2004 and Brink et al., 2010). Studies involving Australian football players had their training load monitored for the full-season (Moreira et al., 2015 and Ritchie et al., 2015). There were studies that monitored the training load of a professional soccer team for an entire season (Malone et al., 2015a). However, the training load data from matches were not used in the analysis (Malone et al., 2015a). As the competitive season has periods of high fixture congestion, the training load pattern may differ according to these periods. Coaches and sports scientists may also alter training programmes and weekly microcycle plans when preparing for 2 matches in a week instead of the typical 1 match. Therefore, the aim of the current study is to quantify the training loads used by an English League 1 professional soccer club across a competitive season. This information would provide details of the training periodisation strategies utilised in professional soccer. As the season progresses, there would be periods of high fixture congestion, hence, quantification of training load data would allow coaches and sport scientists to plan training programmes more effectively so that players are optimally prepared for the upcoming matches.

Besides the high-intensity runs and sprints the players have to perform during matches, they also have to change directions, perform jumps and tackles which will impose significant disturbances in multiple physiological systems (de Hoyo et al., 2016). Inevitably players will experience fatigue, a decrease in physical performance associated with an increase in the real and/or perceived difficulty of the task or exercise (MacIntosh et al., 2006). Fatigue can be observed during matches via reductions in work rate following demanding periods of a match and cumulative reductions in work rate during the latter stages of the match (Mohr et al., 2003 and Rampinini et al., 2011). The fatigue from matches may continue post-exercise and may take up to 72 hours for players to recover (Ascensao et al., 2008 and Rollo et al., 2014). The competitive schedule in modern soccer does not allow much time for recovery as elite teams have to play multiple matches with minimal recovery time between successive matches.

Fatigue after a competitive match was initially linked to the energy depletion, perturbations to peripheral homeostasis and damage to muscle tissue (Ekblom, 1986, Ispirlidis et al., 2008, and Nedelec et al., 2012). Damage muscle tissues would result in the reduction of force generating capacities (Thomas et al., 2017). The reductions in maximum voluntary contraction post-exercise were attributed to neuromuscular fatigue; a consequence of impairment in contractile function (peripheral fatigue) and/or the ability of the central nervous system to activate the muscle (central fatigue) (Gandevia, 2001). Recent research had pointed out dissociated rates between the temporal pattern of recovery of muscle fatigue and markers of exercise-induced muscle damage following intermittent sprint exercise (Poinotn et al., 2012 and Minett and Duffield, 2014). It was then suggested that processes within the central nervous system could contribute to the resolution of fatigue following match-play (Minett and Duffield, 2014). Hence, it was later found that impairments of the central nervous system, measured via reductions in voluntary activation, were evident after a stimulated match and persisted for 72 hours (Thomas et al., 2017). A reduction in voluntary activation in the muscles were also observed following a competitive soccer match which persisted after 48 hours (Rampinini et al., 2017).

An understanding of the mechanisms of neuromuscular fatigue and the time-scale of recovery are important practical implications to optimally manage the recovery and training processes, player rotation strategies during periods of high fixture congestion and for those involved in scheduling matches (Brownstein et al., 2017). Therefore, the secondary aim of this study was to compare the training load of training sessions of weeks in preparation for 1 match against weeks to prepare for 2 matches and to investigate the effect of training and match loads on neuromuscular function. By doing so, coaches and sports scientists would be able to identify the impact of the training sessions on the players' fatigue status. With this knowledge, the coaches and sport scientists could periodise training cycles according to the training goals and provide them with the optimal training plan.

It was hypothesised that:
$H1_0$: there will be no significant difference in training load metrics across the course of the competitive season.
$H1_1$: there would be a significant difference in training load metrics during the competitive season.

$H2_0$: there will be a significant difference in the training load metrics between weekly microcycles with 1 match and 2 matches.
$H2_1$: there will be no significant differences in the training load metrics between weekly microcycles with 1 match and 2 matches.

$H3_0$: there will be a correlation between the training load in a 7-day microcycle to the jump height difference.
$H3_1$: there will be no correlation between the training load in a 7-day microcycle to the jump height difference.

4.2. Methodology

4.2.1. Experimental Design

Training load data was collected from 24 professional outfield soccer players competing in League One (third-tier English soccer league). The players were aged 25 ± 4 years old, weigh 80.2 ± 7.8 kg and were 181 ± 6 m tall. The data were compiled over a 40-week period, spanning from the start to the end of the 2018-2019 domestic season. The data were summed and averaged at the end of each week for weekly analysis. An average week would consist of training sessions on Monday, Tuesday, Thursday and Fridays ending with a match on Saturday. Wednesdays and Sundays are rest days. Goalkeepers were excluded from the data analysis. The full duration of each training session was used for the analysis, including the team's warm up sessions and all training drills. The data for this study were collected at the club's outdoor training grounds. Match data was collected via the GPS as well. All players were made aware of the study and provided written consent. This study was approved by the University Ethics Committee of the University of Kent.

The collection of GPS metrics from the players were as mentioned in Chapter 3.

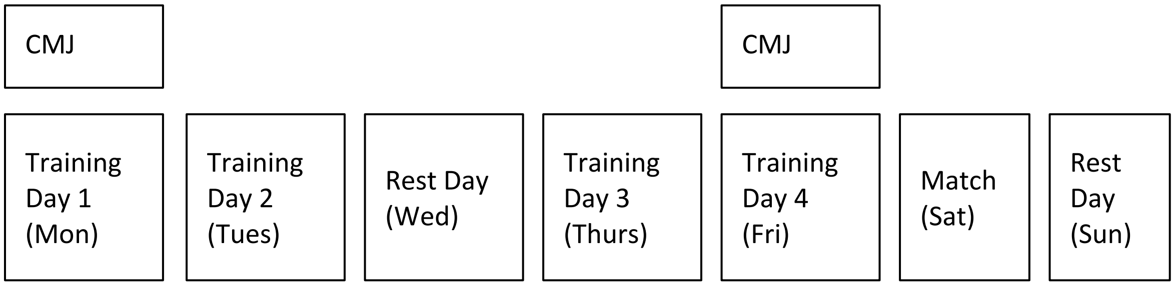


Figure 4. Typical Training Week.

4.2.2. Counter Movement Jump

The players performed counter movement jumps as an assessment for neuromuscular fatigue using a jump mat (Probotics Inc., Huntsville, United States). The jumps were performed on the days as indicated in Figure 4, before training commenced. The variables recorded from the jumps were the jump height (m) and flight time (seconds). To perform the jumps, the players had to bend both knees to 90° and jump as high as possible while having their knees extended and hands on their hips throughout the whole jump. They were required to perform 3 submaximal jumps as a warm up before performing 3 maximal jumps. The jump with the greatest height and flight time from the 3 maximal jumps would be selected for analysis.

4.2.2. Data Analysis

Over the course of the season, some players were unable to provide full sets of training and match data due to various reasons including long-term injury (n = 4), players transferred out (n = 3) and players transferred in (n = 5). So, data from 12 players were deemed suitable for analysis. The data of these players were selected on the basis that they had completed most of the training sessions over the course of the season and missed less than 2 weeks' worth of training, which was the main criteria for their selection. Their data was then averaged every 5 weeks throughout the competitive season. The training load data was averaged every 5 weeks to ensure an equal number of weeks were accounted for as the data was analysed as shown in Figure 5.

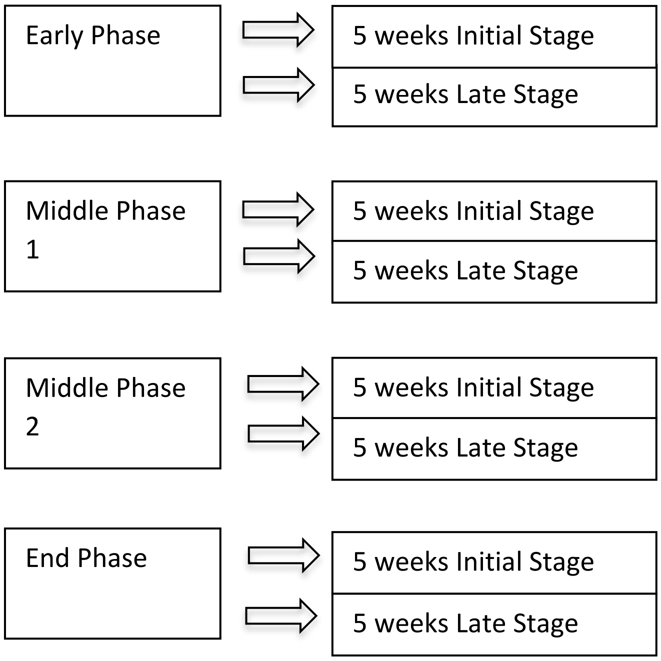


Figure 5. Outline of experimental design. Pre-season block represents training load data compiled during preseason. 'Initial Stage' blocks represent the first 5 weeks of a phase of the competitive season. 'Late Stage' blocks represent the final 5 weeks of a phase of the competitive season.

The division of the season into 4 phases allowed for the investigation of loading patterns incorporated in this training unit (Malone et al., 2015a). After each training session and match, the units were collected and the data downloaded using the respective software package (GPSports SPI IQ Team AMS software, Canberra, Australia) on a personal computer and exported for analysis. The GPS receiver (GPSport SPI HPU Station, Canberra, Australia) and software application (GPSport SPI RealTime software, Canberra, Australia) were used to identify the exact start and end times of the training sessions and matches.

During the season, there were periods where the team had to play two competitive matches in a week instead of the typical one competitive match per week. The training load for each training session for 4 random weeks where the team had played 2 matches were selected to be compared against 4 random weeks where the team played 1 match. The data for each training load variable were compiled and averaged for each player and compared between the 2 different preparatory weeks.

4.2.3. Statistical Analysis

The criteria for players to have their training load data analysed was to miss a maximum of 2 weeks of training. The training load variables that were analysed were total distance covered, high-speed distance covered and New Body Load. To identify changes in training load data between the different blocks throughout the season, data from the players that had met the criteria was analysed using repeated measures analysis of variance (ANOVA). All data are presented as mean ± standard deviation with $P < 0.05$ indicating statistical significance.

In order to consider the effect of fixture congestion on training load, data of all the players (n = 20) were used to compare weeks with 1 match against those with 2 matches. The data were analysed using the paired sample T-test. The data for each player were averaged over the course of the selected 4 weeks. This process was done for weeks with 1 match per week and 2 matches per week. The averaged data were compared against each other. The confidence intervals were set at 95%. The level of significance was set at $P<0.05$. In the event where there is a statistical difference between the training load, a paired sample T-test is performed on the training load data of the first match (Match 1) and second match (Match 2) of the weeks with 2 matches.

Countermovement jump data week 18 to week 40 were averaged and used to determine the relationship between training load data and height and flight time using Pearson product-moment correlations. The level of significance was set at $p < 0.05$. Data are presented as mean ± standard deviation unless stated otherwise.

All statistical analyses were performed on IBM SPSS Statistics 24 (SPSS Inc, Chicago, United States).

4.3. Results

4.3.1 Changes in Training Load Over the Season

As shown in Figure 6A, the total training distance did significantly change over the course of the season ($F (7, 77) = 2.177$, $p = 0.045$, effect size = 0.38). The training block with the highest distance covered was in late stage of middle phase 1 (22334.42 ± 2812.92 m) and the least accumulated was in late stage of the end phase (16861.93 ± 4250.13 m). Follow up tests indicate a statistical difference in between the initial stage of the early phase with the late stage of the end phase ($p = 0.048$, 95% Confidence Interval [38.83 m to 9410.25 m], effect size = 0.92). There was a significant difference between the late stage of the early phase with the initial stage of the end phase ($p = 0.038$, 95% Confidence Interval [102.21m to 2883.45m], effect size = 0.27) and the late stage of the end phase ($p = 0.023$, 95% Confidence Interval [841.75 m to 9277.96m], effect size = 1.04). The initial stage of the middle phase 1 was significantly different to the late stage of middle phase 1 ($p = 0.007$, 95% Confidence Interval [-6380.19 m to -1313.75 m], effect size = 0.99). The late stage of middle phase 1 was also significantly different to the late stage of the end phase ($p = 0.001$, 95% Confidence Interval [2878.5 m to 8066.48 m], effect size = 1.52). The late stage of middle phase 2 was significantly different to the late stage of end phase ($p = 0.008$, 95% Confidence Interval [-5991.27 m to -1134.44 m], effect size = 0.95).

The amount of high-speed distance covered changed significantly during the course of the season ($F (7, 77) = 3.949$, $p = 0.001$, effect size = 0.264), with late stage of middle phase 1 (1700.90 ± 514.98 m) having the greatest, with the least accumulated during the late stage of the end phase (1006.34 ± 354.45 m). Follow-up tests indicate a statistical difference between the total high-speed distance covered during initial stage of the early phase of the season compared against the late stage of the end phase ($p = 0.012$, 95% Confidence Interval [123.62 m to 809.71m], effect size = 1.03). Late stage of the early phase of the season was statistically different to the late stage of middle phase 2 ($p = 0.049$, 95% Confidence Interval [1.96 m to 538.79 m], effect size = 0.65) and the late stage of end phase ($p = 0.002$, 95% Confidence Interval [262.92 m to 877.84 m], effect size = 1.35). The initial stage of middle phase 1 was statistically different to the late stage of middle phase 1 ($p = 0.004$, 95% Confidence Interval [-625.13 m to -153.84 m], effect size = 0.73) and the late stage of the end phase ($p = 0.035$, 95% Confidence Interval [25.54 m to 584.61 m], effect size = 0.66). The late stage of middle phase 1 was statistically different to the late stage of middle phase 2 ($p = 0.013$, 95% Confidence Interval [102.48 m to 686.63 m], effect size = -0.91) and late stage of end phase ($p = 0.0001$, 95% Confidence Interval [392.94 m to 996.19 m], effect size = 1.57). The late stage of middle phase 2 was statistically different to the late stage of the end phase ($p = 0.003$, 95% Confidence Interval [122.029 m to 477.98m], effect size = 0.87). The initial stage of the end phase was statistically different to the late stage of the end phase ($p = 0.002$, 95% Confidence Interval [238.19 m to 849.50 m], effect size = 1.19).

Figure 6C illustrates that there was no significant change in the New Body Load accumulated throughout the season, ($F (7, 77) = 1.875$, $p = 0.085$).

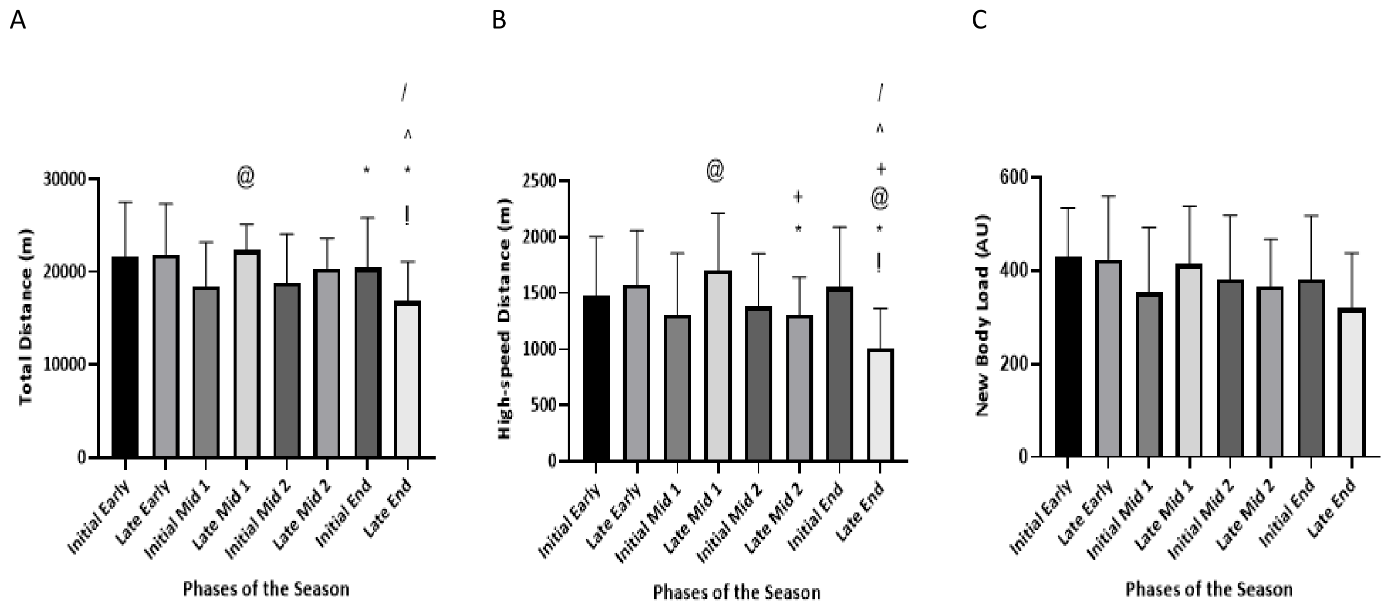


Figure 6. Changes of Training Load over the course of the season. A: Changes in total distance covered. B: Changes in high-speed distance covered. C: Changes in New Body Load. Key: ! represents significant differences with the initial stage of the early phase, * represents significant differences with the late stage of the early phase,@ represents significant changes with initial stage of middle phase 1, + represents significant difference with late stage of middle phase 1, ^ represents significant differences with late stage of the middle phase 2 and / represents significant with the initial stage of the end phase.

	Total Distance Covered over the Course of the Season								Changes in Total Distance Covered throughout the Season					
Player	Initial Early	Late Early	Initial Mid 1	Late Mid 1	Initial Mid 2	Late Mid 2	Initial End	Late End	Initial Early - Late End	Late Early - Initial End	Late Early - Late End	Initial Mid 1 - Late Mid 1	Late Mid 2 - Late End	Initial End - Late End
CB	25528.09	24630.65	23978.77	19567.81	10745.05	23396.13	22165.94	18893.52	6634.57	2464.72	5737.13	4410.96	674.29	3272.41
CF1	24204.05	25230.79	25847.06	27381.77	13116.35	23177.55	26696.34	18715.62	5488.43	-1465.55	6515.17	-1534.70	8666.15	7980.72
CF2	26358.06	23466.18	14309.03	18896.96	21539.00	22315.35	24101.27	20921.57	5436.49	-635.09	2544.61	-4587.93	-2024.61	3179.70
CM1	15685.95	15267.19	21368.10	24830.58	21687.22	17506.26	16597.57	16453.59	-767.64	-1330.38	-1186.40	-3462.48	8377.00	143.98
CM2	28748.63	7196.53	17484.47	21603.22	13168.82	15971.96	5921.36	16201.36	12547.27	1275.17	-9004.83	-4118.76	5401.87	-10279.99
CM3	23525.80	25871.13	23617.23	24524.83	25119.94	26740.92	25045.96	19686.03	3839.77	825.18	6185.11	-907.60	4838.80	5359.93
CM4	12495.66	23062.30	15083.73	23205.72	14726.58	22797.38	19350.34	17224.89	-4729.23	3711.96	5837.41	-8121.99	5980.83	2125.45
CM5	10688.23	25992.52	15047.19	23978.56	23661.75	19987.83	20675.96	19780.04	-9091.81	5316.57	6212.48	-8931.38	4198.52	895.91
CM6	22889.44	24351.40	10599.34	18279.36	27129.01	17573.70	22368.07	4416.28	18473.16	1983.33	19935.12	-7680.02	13863.08	17951.79
WB1	18249.32	24198.28	21098.99	23202.69	16113.35	19132.85	22101.66	15570.96	2678.36	2096.62	8627.32	-2103.69	7631.72	6530.70
WB2	27487.45	21555.38	14848.51	23220.96	20170.55	18074.39	17526.31	17779.85	9707.60	4029.07	3775.53	-8372.44	5441.11	-253.54
WB3	23177.01	22239.12	18567.05	19320.63	18768.50	18423.12	22596.54	16699.48	6477.53	-357.42	5539.64	-753.59	2621.15	5897.06
AVG	21586.47	21921.79	18487.46	22334.42	18828.84	20424.79	20428.94	16861.93	4724.54	1492.85	5059.86	-3846.97	5472.49	3567.01
STD	5928.59	5448.76	4701.14	2812.92	5251.54	3210.33	5420.13	4250.13	7374.78	2188.71	6638.82	3987.00	4082.65	6545.87

Table 3. Total distance covered over the course of the season and significant changes.

	High-speed Distance Covered Over the Course of the Season								Changes in High-speed Distance throughout the Season								
Player	Initial Early	Late Early	Initial Mid 1	Late Mid 1	Initial Mid 2	Late Mid 2	Initial End	Late End	Initial Early - Late End	Late Early - Late Mid 2	Late Early - Late End	Initial Mid 1 - Late Mid 1	Initial Mid 1 - Late End	Late Mid 1 - Late Mid 2	Late Mid 1 - Late End	Late Mid 2 - Late End	Initial End - Late End
CB	1241.88	1155.31	1241.94	1287.40	712.92	947.39	1029.30	729.30	512.58	207.92	426.01	-45.46	512.65	340.01	558.10	218.09	300.00
CF1	2234.57	2278.20	2594.24	2794.93	1184.15	1922.85	2659.64	1708.58	526.00	355.35	569.63	-200.69	885.66	872.08	1086.35	214.27	951.07
CF2	2117.76	1650.10	1037.83	1016.64	1406.91	1555.92	1821.77	1340.28	777.48	94.17	309.82	21.19	-302.45	-539.28	-323.64	215.64	481.49
CM1	1175.72	1101.16	1677.37	2523.21	1929.25	1313.59	1253.14	988.02	187.69	-212.43	113.14	-845.84	689.34	1209.61	1535.18	325.57	265.12
CM2	1712.97	455.71	1085.31	1236.15	633.78	1153.61	464.21	767.05	945.91	-697.90	-311.35	-150.84	318.26	82.54	469.10	386.55	-302.84
CM3	1781.76	1940.71	1876.77	1809.32	1823.51	1883.45	1957.27	1118.19	663.57	57.26	822.52	67.45	758.58	-74.13	691.13	765.26	839.08
CM4	754.40	1738.55	634.98	1548.48	1099.73	1359.33	1435.24	1157.40	-403.01	379.21	581.14	-913.50	-522.43	189.14	391.07	201.93	277.83
CM5	600.75	1765.40	849.62	1537.31	1342.44	1206.77	1516.37	908.76	-308.01	558.63	856.64	-687.69	-59.14	330.54	628.55	298.01	607.61
CM6	1640.06	1963.57	827.34	1562.98	2232.62	1152.54	1946.88	250.95	1389.10	811.03	1712.61	-735.64	576.39	410.44	1312.03	901.59	1695.92
WB1	1022.10	1812.18	1574.08	1834.56	1207.99	1246.81	1630.89	1124.20	-102.10	565.37	687.98	-260.47	449.88	587.75	710.36	122.61	506.69
WB2	2016.35	1480.17	1048.09	1830.34	1706.78	1089.59	1440.17	1073.04	943.31	390.58	407.12	-782.25	-24.95	740.76	757.30	16.54	367.13
WB3	1377.77	1579.62	1289.41	1429.54	1278.80	844.30	1447.36	910.32	467.45	735.32	669.30	-140.13	379.09	585.24	519.22	-66.02	537.04
AVG	1473.01	1576.72	1311.42	1700.90	1379.91	1306.35	1550.19	1006.34	466.67	270.38	570.38	-389.49	305.07	394.56	694.56	300.00	543.84
STD	531.14	483.04	545.56	514.98	476.05	334.13	540.22	354.45	539.91	422.45	483.91	370.88	439.95	459.69	474.72	280.11	481.07

Table 4. High-speed distance covered over the course of the season and the significant changes.

4.3.2 Training load during weeks with 1 vs 2 matches

Training load per week was compared during weeks when players had 1 match vs 2 matches. In order to compare the training load, match data was removed. As shown in figure 7A, there was a significant difference in the total distance covered by the players when preparing for 1 match per week versus 2 matches per week (1 match = 14076.16 ± 1569.24 m vs. 2 matches = 7874.35 ± 1923.01 m; t (3) =3.571, p = 0.038, 95% Confidence Interval of Difference [674.40 m to 11729.23 m], effect size = 3.53).

Figure 7B presents players covering less high-speed distance during the training sessions when preparing for 1 match per week versus 2 matches per week (1 match = 781.49 ± 109.89 m vs. 2 matches = 413.99 ± 91.87 m; t (3) = 4.445, p = 0.021, 95% Confidence Interval of Difference [104.39 m to 630.60 m], effect size = 3.63).

On average, the players accumulated more New Body Load during training sessions in preparation for 1 match per week against preparing for 2 matches per week (1 match = 281.82 ± 35.36 AU vs 2 matches = 135.93 ± 12.02 AU). The difference between the New Body Load in preparation for 1 match per week against 2 matches per week was significant (t (3) = 11.78, p = 0.001, 95% Confidence Interval of Difference [106.47 AU to 185.31 AU], effect size = 5.52).

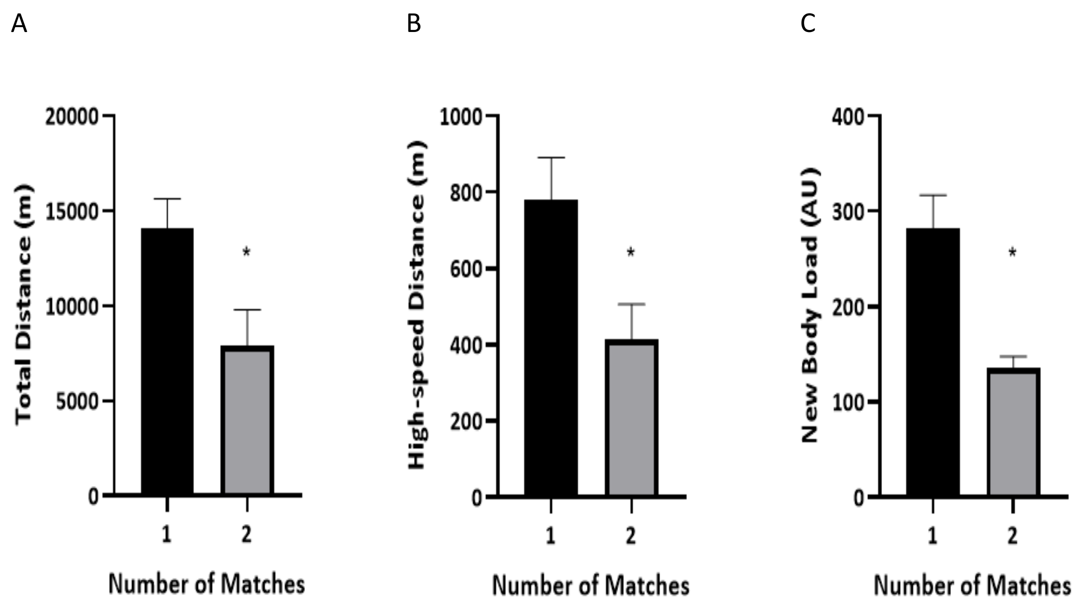


Figure 7. Changes in Training Load in training sessions in preparation for weeks with 1 match and 2 matches. Figure 6A: Comparison between total distance covered from training sessions in preparation for 1 match per week against 2 matches per week. Figure 6B: Comparison between high-speed distance covered from training sessions in preparation for 1 match per week against 2 matches per week. Figure 6C: Comparison between New Body Load accumulated from training sessions in preparation for 1 match per week against 2 matches per week. Key: * represents significantly lower than match 1.

4.3.3. Comparison between training load from matches

Taking from an average of 4 different weeks of matches analysed, Figure 8A shows that Match 1 recorded the highest distance covered (6249.83 ± 1220.15 m) while the least total distance covered was in Match 3 (5515.18 ± 277.24 m). The mean difference was not statistically significant (F (2, 6) = 0.375, p = 0.702).

As shown in Figure 8B, Match 3 recorded the most high-speed distance covered (555.06 ± 329.15 m) and the Match 2 recorded the least (516 ± 117.41 m). The mean difference was not statistically significant (F (2, 6) = 0.049, p = 0.952).

Figure 8C shows that the match with the highest New Body Load was Match 2 (123.57 ± 24.61 AU) and the match with the least New Body Load recorded was Match 1 (105.62 ± 7.91 AU). There were no statistically significant differences between the means (F (2, 6) = 1.584, p = 0.28)

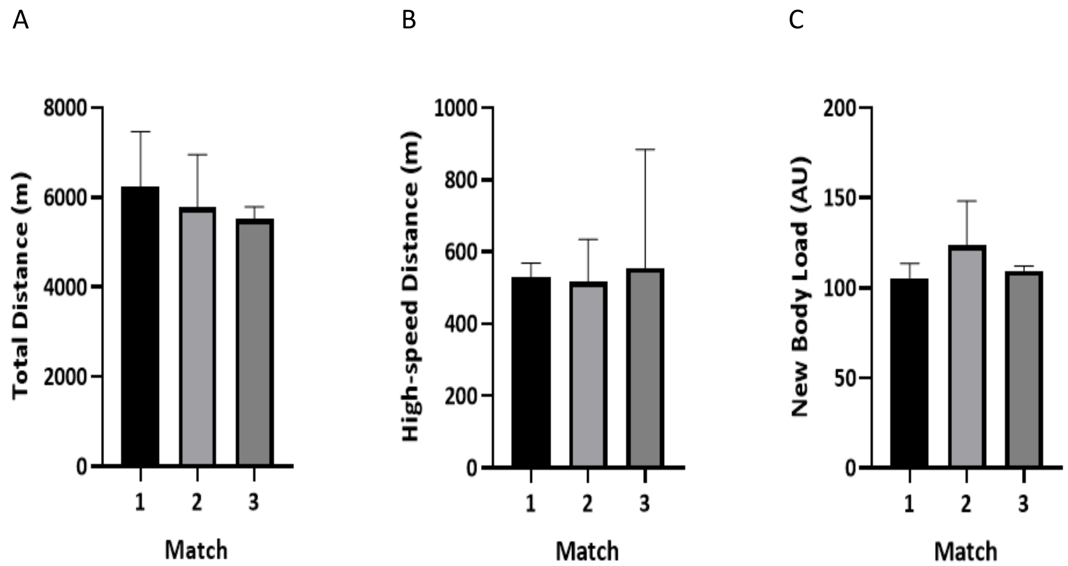


Figure 8. Comparison between training load from matches. A: Total distance covered in the matches. B: High-speed distance covered in the matches. C: New Body Load accumulated in the matches. Match 1, only one match was played within the week. Match 2 is the first match played in a week where there are 2 matches. Match 3 is the second match played during a week with 2 matches.

4.3.4. Comparison between training load accumulated (training sessions and matches) in weeks with 1 match versus weeks with 2 matches

When adding the training load data from the training sessions and matches of the respective weeks, Figure 9A presents weeks with 1 match recorded higher total distances covered than weeks with 2 matches (1 match = 19719.09 ± 1886.42 m versus 2 matches = 17900.97 ± 1759.69 m; *t* (3) = 1.366, p = 0.265).

As shown in Figure 9B, Weeks with 1 match were less than weeks with 2 matches in terms of high-speed distance covered (1 match = 1255.04 ± 110.71 m versus 2 matches = 1360.23 ± 396.85 m; *t* (3) = -0.429, p = 0.697).

Figure 9C shows that weeks with 1 match accumulated more New Body Load than weeks with 2 matches (1 match = 379.51 ± 40.64 AU versus 2 matches = 333.18 ± 29.32 AU; *t* (3) = 2.977, p = 0.59).

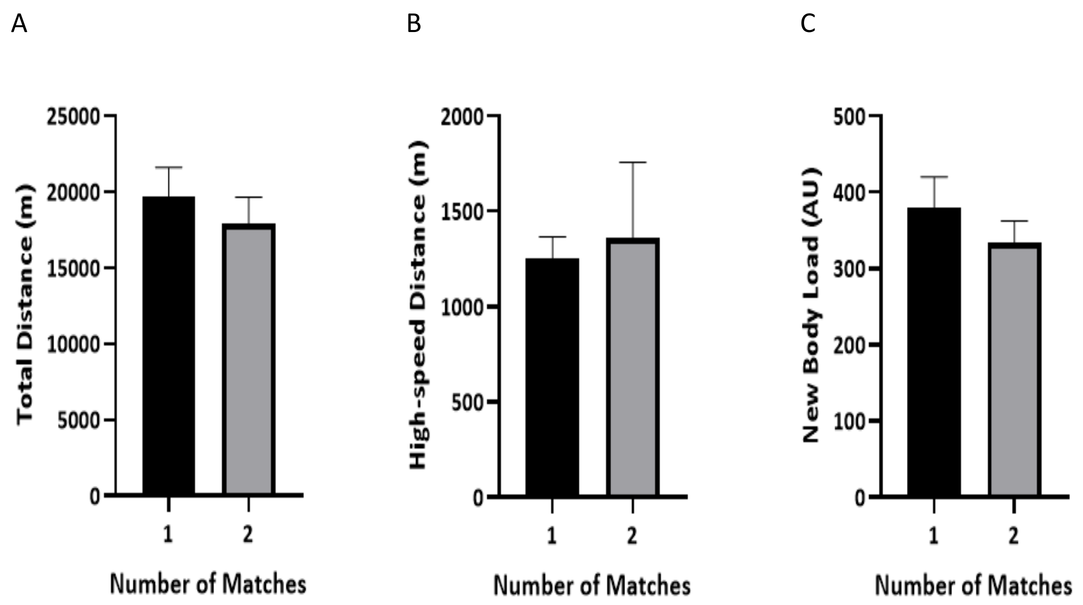


Figure 9. Comparison between training load accumulated (training sessions and matches) in weeks with 1 match versus weeks with 2 matches. A: Total distance covered in a week. B: Total high-speed distance covered in a week. C: Total New Body Load accumulated in a week.

4.3.5. Correlation between Training Load and Counter Movement Jump

As shown in Figure 10, the total distance accumulated in the 7-day period was not correlated to the jump height difference (r = -0.001, p = 0.995). Moreover, there were no correlations between jump height difference and both total high-speed distances accumulated (r = 0.07, p = 0.547), or new body load (r = 0.101, p = 0.386), in the 7-day period.

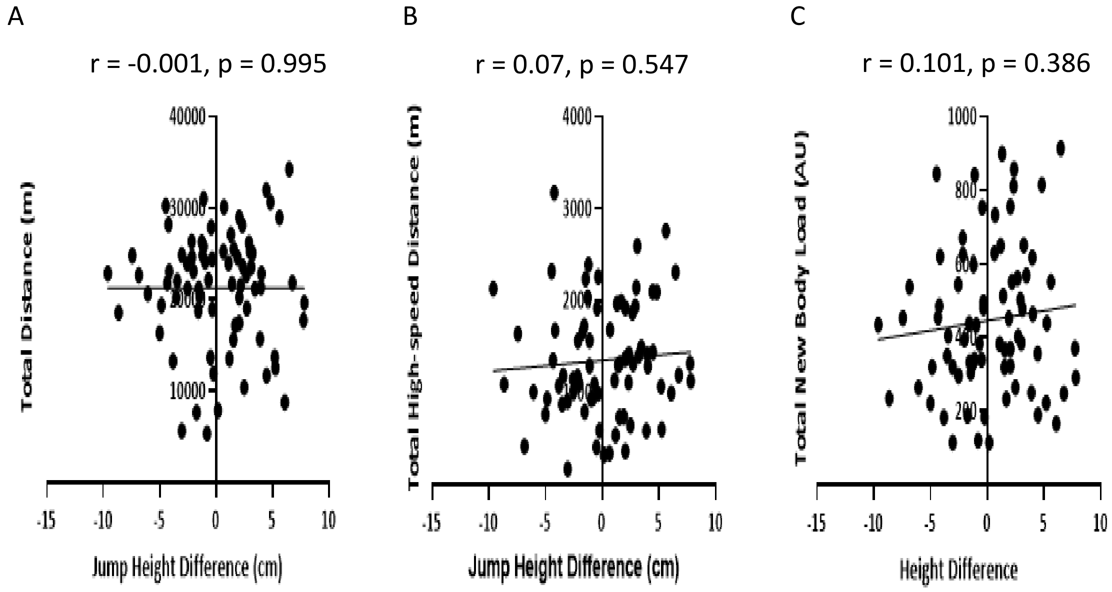


Figure 10. Correlation between jump height difference and training load in a 7-day microcycle. A: Correlation between jump height difference and total distance covered. B: Correlation between jump height and high-speed distance covered. C: Correlation between jump height difference and New Body Load.

4.3.6. Change in Training Load and Counter Movement Jump performance

As shown in Figure 11, the change in total distance covered does not correlate with the change in CMJ performance (r = 0.150, p = 0.196). The change in high-speed distance covered does not correlate with the CMJ performance (r = -0.130, p = 0.262). The change in New Body Load accumulated does not correlate with the change in CMJ performance (r = -0.125, p = 0.281).

A B C

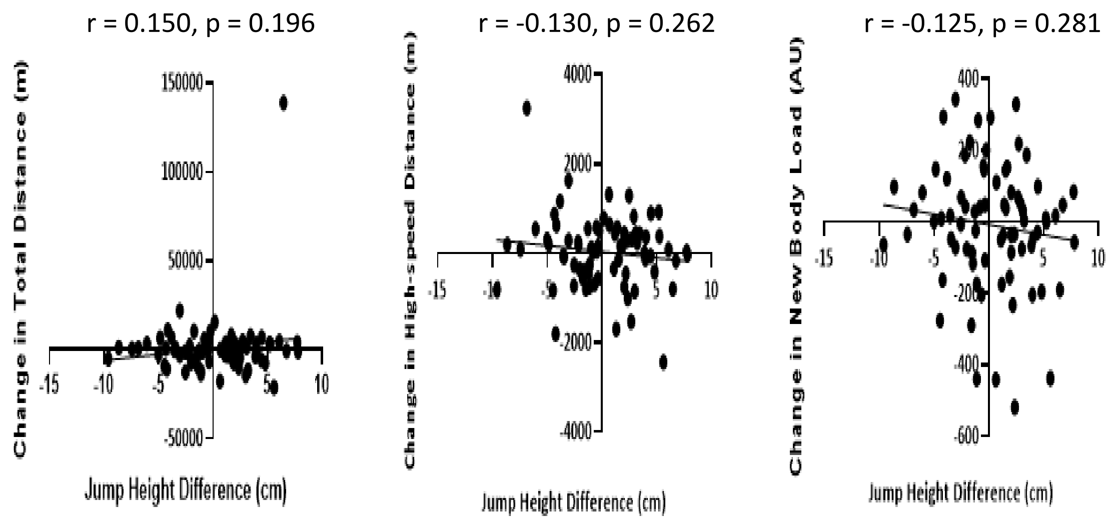


Figure 11. Change in training load and change in jump performance. A: Change in total distance covered. B: Change in high-speed distance covered. C: Change in New Body Load accumulated.

4.4 Discussion

The aim of the study was to quantify and evaluate training loads used by a professional soccer club across a competitive season. The in-season was divided into mesocycles of 5 weeks with changes in the training load pattern were investigated across the period. Results demonstrate that there was a significant difference in the total distance covered and high-speed distance covered across the season, although no significant changes were found in the New Body Load. As such, $H1_0$ is rejected and the alternative hypothesis is accepted. Furthermore, results showed significant differences in the training load metrics between weekly microcycles with 1 match and 2 matches per week, so $H2_0$ is accepted. Finally, no correlation was found between the training load in a 7-day microcycle and countermovement jump height, thus $H3_0$ is accepted.

4.4.1. Changes in training load across the competitive season

The current study had shown that there were significant changes in the total distance and high-speed distance covered by the players throughout the season. A previous study quantifying the training load in an Australian football team found the weekly training load was similar across all the mesocycles during the "in-season" period (Ritchie et al., 2016). It was suggested that the coaches plan training sessions that facilitate the preparation for and recovery from competition, given the 1-game per week nature of the Australian Football League (Slattery et al., 2012). Similar results were observed where a study on elite soccer players showed a reduction in total distance covered when comparing between the start of the season and the final mesoycle of the season (5734 m vs. 4495 m) (Malone et al., 2015a). This is most likely influenced by external factors such as periods of fixture congestion (Malone et al., 2015a). With the high number of fixtures in these periods, the players' total coverage in a week would increase. Hence, the duration of training sessions was reduced when there were more matches in the week so that training load would decrease, allowing more recovery for the players. Similarly, a study on Australian football players found that the distribution of training intensity was maintained during the in-season phase, but with increases in the proportion of time spent training at higher intensities compared to the distribution of training intensity in pre-season (Moreira et al., 2015). The authors state that the increase in high intensity training was likely due to the increased contribution of match load to the overall training dose in the competition season (Moreira et al., 2015). However, soccer coaches must manipulate and periodise training sessions accordingly during the available time to maintain physical fitness or longitudinal improvements (Malone et al., 2015a). Previous research had suggested that limited variation in training load may increase the risk of illness and overtraining (Foster et al., 2001). The findings of the current study would suggest a lack of training load variation at different points of the season.

A sharp decline in the late stage of the end phase of the season was due to the reduction of training sessions altogether, this may also suggest efforts to provide the players with more recovery time. The reduction in training sessions would result in a low accumulation of training load. This method of tapering was also used in previous studies (Child et al., 2000; Johns et al., 1992; McConell et al., 1993). However, it was reported that reduction in training frequency among distance runners had found that decreasing training load via reducing training frequency did not improve running performance despite maintaining their aerobic capacity (McConell et al., 1993). Hence, a reduction in training duration instead of training frequency may have been a more ideal method tapering strategy to maintain running performance in matches.

4.4.2 Alteration of Training Load in Preparation for 1 match per week versus 2 matches per week

Training plans and periodisation are usually structured into weekly microcycles during the in-season phases of professional soccer (Malone et al., 2015a). Overall training success is highly dependent on the planning in the microcycle (Stone et al., 2007). The current study investigated the alteration in a weekly microcycle when preparing for 1 match versus preparation for 2 matches in a week. When considering training sessions in isolation there was a significant difference in the training load between weeks. Specifically, players covered more total distance, high-speed distance, and accumulated more New Body Load during training sessions in weeks with 1 match versus weeks with 2 matches. The reduction in training loads during weeks with 2 matches demonstrate the coaches' application of tapering during training sessions in order to accommodate for the extra load encountered during the second match. Interestingly, the total accumulated training load (training sessions and match data) in weeks with 1 match versus 2 matches was not significantly different, suggesting that the coaches were indeed able to appropriately adjust training. A study on the weekly training load profile of elite basketball players also demonstrated a tapering approach as the workload of the players reduced 3 days before a game (1 match per week) (Manzi et al., 2010). When preparing for 2 matches per week, a similar approach was also applied where the training load before the matches were low (Manzi et al., 2010). In the current study, tapering was done by reducing the training load. The intensity of the training sessions was maintained at the level of training sessions in preparation for 1 match per week. As illustrated in Figure 6, the pattern of the high-distance covered and the New Body Load accumulated were reflected in the total distance covered, indicating that intensity of training sessions was maintained according to the training volume. The reduction of training load can be done by alteration of training volume, intensity and frequency (Wenger et al., 1986). Reduction in training load via reducing the time of training sessions was much preferred to reducing the frequency of training sessions as the latter strategy was reported to result in lack of improvement in sporting performance (Bousquet et al., 2007). However, training load should not be reduced at the expense of training intensity (Mujika and Padilla, 2003). It was suggested that training intensity should be maintained despite a reduction in training load to maintain training-adaptations during the taper (Mujika et al., 2004). The lack of variation in the training over a longitudinal period may result in inadequate recovery time and cause overreaching among the players (Foster et al., 2001).

As illustrated in Figure 7, when comparing the workload from matches against each other from their respective weeks (1 match per week vs 1st match of the double game week, vs 2nd match of the double game week), there were no significant differences across the metric. These results were similar with previous findings (Carling et al., 2012, Dellal et al., 2015 and Lago-Penas et al., 2011). The lack of variation between matches reported in previous studies supports the notion that time-motion demands in professional soccer are somewhat consistent (Folgado et al., 2015). When the training load data from training sessions and matches of each microcycle week were added together, no significant differences were found between weeks with 1 match against those with 2 matches. These results suggest that the training sessions in microcycles were manipulated so that each microcycle ends with all the players reaching a similar amount of training load. Similar to the current study, a study reported weekly total accumulated distances to be higher in weeks preparing for 2 matches compared to preparing for 1 match in a week (Andersson et al., 2016). Due to the requirement in 2 matches, the players accumulated more duration in activity as well as spent more time in the high-speed zones (Andersson et al., 2016). However, it is important to highlight that player rotation strategies were not taken into account in the current study. Further information is necessary to identify the frequency of individual players actually playing and completing matches over a short and/or prolonged period of fixture congestion.

The results from the quantification of the training load data across the season appears to contradict the results of the training load data of the weeks in preparation for 1 match versus 2 matches. This contradiction may be because of the difference in analysis of the mesocycles in the quantification of training load data across the whole season as compared to analysing individual weeks selected with 1 match and 2 matches. The stages of the season have a mixture of 1 match and 2 matches within each stage which may have skewed the data and results in showing that there is no manipulation of training load volume in preparation for the matches. The distribution of matches was not equal throughout the season, hence causing some mesocycles to have more matches than others, skewing the data. However, isolated analysis of the training load in preparation for 1 match versus 2 matches in a week showed otherwise. It may be because of the comparison between a whole season's worth of data versus data from isolated weeks of the season. This is due to the volume of the data across of the season masks these more subtle but critically important variations associated with mesocycle variation. Therefore, it is important for coaches and sports scientists to include both longer term trends and shorter week-to-week data in their analysis of training load.

The congestion of matches would potentially induce residual fatigue and also increase the risk of injury because of the lack of time to recover for the players (Dupont et al., 2010). Previous research has shown that muscle soreness occurring during the post-match period indicates exercise-induced microtrauma and a concomitant elevation in muscle damage (Nedelec et al., 2013). In theory, these effects would cause the decline in subsequent competitive physical performance if the recovery time between matches were too short. Players required 96 to 120 hours of recovery for them to achieve pre-match results in 20 m sprint performance and to normalise blood markers of muscle damage and inflammation (Ispirlidis et al., 2008). However, the current study showed no significant differences in high-speed distance and New Body Load between the matches. These results were similar with those of a previous study where the high-speed distance did not change between 2 matches played within 4 days (Dupont et al., 2010). Within the current study, players' ability to recover in a short timeframe were facilitated by scientists promoting recovery methods such as ice baths immediately after matches (Vaile et al., 2008), using compression garments (Ispirlidis et al., 2008) and consuming meals with high amounts of carbohydrate until the following match (Dupont et al., 2010).

4.4.3. Neuromuscular Fatigue of Players

The neuromuscular fatigue of the players was assessed using the countermovement jump (CMJ) test. There were, however, no correlations between the jumps and the training load between the jumps, which was set at 7 days. There were also no correlations between the change in jump height difference and training load difference. The results were similar to that of a previous study where elite youth soccer players performed jumps before and after a training session (Malone et al., 2015b). This suggests that the training load did not influence the change in CMJ performance. It was suggested that there were no changes in the countermovement jump height because the players were prescribed training programmes that focus on the maintenance of their fitness levels and ensuring players recover sufficiently before the following matches during the in-season period (Reilly, 2006). Hence, coaches would prefer workloads that optimises recovery while maintaining the players' physiological status as opposed to workloads that induce physiological overload on the players (Viru and Viru, 2001). However, previous research has found significant reductions in CMJ height (-4.4 ± 0.8%) following soccer activity (Andersson et al., 2008).

The lack of change in the CMJ performance could also stem from the test's inability to detect small changes in the force-generating capabilities of muscle (Malone et al., 2015b). However, in the current study, the reduction in CMJ height was approximately -1.0%. As the reduction percentage was lower than the test-retest values of such procedures (Malone et al., 2015b), this makes it difficult to determine whether such changes in neuromuscular function measured by the counter movement jump would affect match performance.

4.4.4. Experimental Limitations

There were a few limitations to the current study. A major limitation was the reduction in sample size as the season progressed. Some of the players sustained long-term injuries or left the club during the transfer period, resulting in incomplete data collection from these players. Besides, when analyses of matches were performed, the weekly training load data of all the players present during the matches were used, including unused substitutes. Although unused substitutes performed the warm-up, and running at the end of most matches, the training load data do not mirror those obtained from playing in actual matches. Moreover, the training load data of all the players were analysed as a whole collective group without segregation based on their positions. Consequently, there was high variability in the data as players of different positions perform differently running performance wise. Finally, the collection of the CMJ data was sporadic in nature, some players were unwilling to perform jumps on days before a match out of fear of injuring themselves. Moreover, some players claimed to be “too tired” from the match to perform the jump tests the day after matches, and so declined participation. Consequently, the sample size of players performing the CMJ tests was also very small.

4.4.5. Practical Implications

This study provides useful information for professional soccer teams in regards to the use of training load. The various combinations of training load variables allow teams to evaluate the patterns observed throughout the season. Sports scientists and coaches can use this information to plan training sessions. This study allows for the generation of reference values for the players when planning training sessions. Coaches and sports scientists also should become more aware of the need to monitor training load more strictly for players to receive sufficient load in preparation for matches. There are some variables that are scarcely researched on, such as the New Body Load. Therefore, further research is needed on these variables to further understand their impact on sporting performance. In preparation for 2 matches in a week, training load should be decreased by reducing the duration of training sessions, not frequency of training sessions in a week. Running performance of the players in the current study had shown that this strategy is a more suitable tapering approach in preparation for matches.

The findings regarding the use of CMJ tests as an assessment for neuromuscular fatigue have several implications for the planning of training structure in soccer teams. The lack of change in the CMJ performance suggested that the accumulated training load across the weekly microcycle was similar throughout the season. This indicated that the coaches plan training sessions with the emphasis on maintaining fitness and recovery in preparation for the next match. There were no signs of physiological overload that could risk the players feeling fatigued going into matches. Another possible implication from these findings is that the use of field-based jumping protocols is not suitable to detect significant physiological changes in the players that could impact their sporting performance. The CMJ can still be used to test for jump height difference. Other methods and tools that are user friendly have to be employed to adequately monitor the physiological changes in the players to maximise their athletic potential. Other methods would include the Wingate anaerobic test and the running anaerobic sprint test. The running anaerobic sprint test is suitable as it is easy to apply and cost effective. This test is suitable for soccer players as they have to perform repeated sprints throughout a whole match.

4.4.6. Conclusion

In conclusion, understanding the importance of each training load variable allows coaches and sports scientists to pinpoint the important variables monitored. Alteration in the training microcycles is important for players to be adequately prepared for matches as well as receive sufficient recovery. In regards to assessing neuromuscular fatigue, other assessment methods have to be taken into consideration. Coaches and sports scientists should combine multiple methods for a more accurate assessment instead of just relying on one type of test.

CHAPTER 5: Quantification of External Training Load and Effect on Hamstring Injury Incidence

5.1. Introduction

Non-contact overuse type muscle injuries are a substantial problem for professional soccer players, making up more than 25% of the total injury absence among high-level European professional soccer clubs (Ekstrand et al., 2011). Moreover, the injury occurrence has been shown to impact professional soccer teams' performance (Hagglund et al., 2013) with more matches drawn or lost compared to matches won, during periods with higher team injury incidence (Ekstrand et al., 2004b). For example, in the women's European Championship in 2005, teams that were eliminated from the group stages had a higher match injury incidence than those that had advanced to the semi-finals of the tournament (Walden et al., 2007). However, no such association was found in the men's tournament in 2004 nor the men's under-19 tournament in 2005 (Walden et al., 2007). At club level soccer, a study among Qatari professional soccer clubs had found a strong correlation between injury incidence in a club and overall performance (Eirale et al., 2013). However, it is important to highlight that there are a significantly lower number of matches and teams in the Qatar Stars League, with 10 teams, compared to major leagues such as the English Premier League and La Liga, with 20 teams in the league (Eirale et al., 2013). In contrast, a study on a French professional team over a 15-season period reported no correlation between the team's final league position and the total injury incidence in a season (Dauty and Collon, 2011). Besides its effects on team performance, injuries also have an economic effect on soccer clubs. An injury to a first-team player in a professional soccer club could cost the club an average of €500 000 (Ekstrand, 2013).

Hamstring strains are the most common subtype of non-contact overuse injuries, representing approximately 12% of all injuries (Ekstrand et al., 2011). A team of 25-player squad would typically 5 to 6 hamstring injuries in a season and the injured players would lose more than 80 days of soccer activities in training and matches (Ekstrand et al., 2011). A 13-year injury surveillance study has found that the rate of hamstring injuries at training while the incidence of hamstring injuries during matches have remained stable over the course of the study period (Ekstrand et al., 2016). The increase in hamstring injury rates during training was suggested to stem from coaches deliberately increasing the intensity of training sessions to mimic the high-intensity demands of an actual match, emphasising on more high-speed running with increased number of accelerations and decelerations which can result in higher risk of hamstring injuries (Ekstrand et al., 2016). Hamstring injury rates in matches remained the same possibly because players are more prepared for matches given the high-intensity training they experience (Ekstrand et al., 2016).

Fatigue had often been suggested to cause overuse injuries in sport (Mair et al., 1996), with most hamstring strain injuries found to occur in the latter stages of matches and training sessions (Ekstrand et al., 2010). As professional soccer players may have to play up to two matches per week, an accumulation of these matches over a short period may leave players experiencing residual fatigue due to insufficient recovery time increasing the risk of injury (Dupont et al., 2010). Research has shown that muscle soreness occurs during the post-match period, an indication of exercise-induced micro-trauma and concomitant increase in muscle damage (Nedelec et al., 2010). A study reported injury incidence to be similar when compared between consecutive matches played with a short interval (≤ 3 days) versus consecutive matches with a longer interval (≥ 4 days) (Bengtsson et al., 2013 and Carling et al., 2010). However, a comparison in injury rates between consecutive matches played within a 4-day period and consecutive matches played within a 6-day period had shown injury rates to increase five-fold from playing twice within 4 days (Dupont et al., 2010). In terms of longer periods of fixture congestion, it has been shown that the total injury incidence from both training and matches may not differ between a prolonged fixture congested period against a non-congested period (Delal et al., 2015).

Monitoring of training load has been used as a method to investigate the level of player fatigue in an attempt to reduce the incidence of hamstring strain injuries (Halson, 2014). Many professional sports clubs utilise self-report questionnaires, GPS to track distances and sport-specific tests as a means to assess the players' preparedness for matches and competition (Taylor et al., 2012).

Monitoring the training load of individual players in a team sport is important as each athlete may respond differently to the same training stimulus (Halson, 2014). Indeed, in an effort to manage fatigue levels within a team, previous research had quantified the absolute workload and correlated this to injury incidence within the team (Gabbett, 2004a; Rogalski et al.; 2013; Colby et al., 2014). Acute workload (the absolute workload performed in a week) and the chronic workload (absolute workload performed in 4 weeks) have been investigated and the acute: chronic workload ratio has been established (Hulin et al., 2016b). The acute: chronic workload ratio has been used to provide a workload index, indicating whether a player's acute workload is greater, equal or less to the chronic workload (Hulin et al., 2016b). Previous research has suggested that players with a higher acute workload than their chronic workload are more susceptible to injury (Hulin et al., 2014). Fast cricket bowlers were reported to have an increase in risk of injury by three-times when their acute bowling workloads doubled their chronic bowling workloads, presenting an acute: chronic workload of 2 or higher (Hulin et al., 2014). The acute: chronic workload ratio since has been used as a predictive tool to predict injuries (Hulin et al., 2016b). Athletes were more susceptible to injuries if (a) they had a high acute chronic workload and a high chronic workload and (b) they had large spikes in their acute workload and their acute: chronic workload ratio was approximately 1.5 or higher (Hulin et al., 2016b). It is suggested that training within the ranges of 0.8 and 1.3 of the acute: chronic workload ratio would keep the risk of injury to a minimum (Soligard et al., 2016)

Research also suggests that a high chronic load could protect players from injury (Hulin et al., 2016a). Rugby players were found less likely to suffer a subsequent injury after recovering from a previous one when they had trained for 18 weeks prior to the first injury (Gabbett and Domrow, 2005). However, players and coaches have to be weary of undertraining and overtraining as they can increase the risk of injury (Cross et al., 2016, Lyman et al., 2001 and Dennis et al., 2003). A study reported that cricket bowlers that bowled fewer deliveries per week with high recovery time between sessions risked getting injured more and those that bowled more deliveries while having little recovery time in between also risk getting injured (Dennis et al., 2003). Therefore, training loads have to be monitored to reduce the risk of injury from both overtraining and undertraining.

A controversial aspect of previous research is the claims that the derivatives of training load were deemed 'predictive' of injury (Hulin et al., 2016a). However, associations with injury and predicting injury are different terms and are analysis that should be used for different purposes (Bahr, 2016). Hence, the aim of the investigation was to evaluate eccentric hamstring strength and injury occurrence in relation to training load data throughout the competitive season. The hypotheses were that:

$H1_0$: eccentric hamstring strength of players with hamstring injuries are lower than those who did not have hamstring injuries
$H1_1$: eccentric hamstring strength of players who injured their hamstrings do not differ from those without hamstring injuries

$H2_0$: players who suffer hamstring injuries had higher acute: chronic workload ratio compared to those without hamstring injuries

$H2_1$: players who have hamstring injuries have an acute: chronic workload ratio that does not differ from those without hamstring injuries.

5.2. Methodology

5.2.1. Experimental Design

The collection of GPS metrics from the players were as mentioned in Chapter 3.

Players were separated into two groups. One group of players who had suffered hamstring injury throughout the season (n = 6) and the other group consisting of players who did not suffer any hamstring injuries throughout the season (n = 14). Players were required to perform an isometric Nordic hamstring curl test every week (Tuesday) after the training session to assess their eccentric hamstring strength. This was conducted throughout the season, but only on weeks they did not have a midweek match.

Figure 12. Typical Training Week

5.2.2. GPS Data Collection

The collection of GPS metrics from the players were as mentioned in Chapter 3.

5.2.3. Nordic Hamstring Curl

The isometric Nordic hamstring curl test was selected as it was found that the Nordic break-point angle, where the athlete can no longer maintain an isometric hold of the eccentric Nordic hamstring curl at its lowest point, is correlated to the eccentric knee-flexor torque (Sconce et al., 2013). The Nordic hamstring curls were done on the glute ham developer – compact model (Strength Shop, Motherwell, Scotland). The players would slowly lower their trunk by knee extension in a controlled manner on the glute ham developer as shown in Figure 13. They lowered themselves without performing isometric contractions 3 times as a warm-up before the eccentric isometric test. They do not have to perform any concentric contraction to get back to the starting position (kneeling position). After the warm-ups, they lowered themselves to the lowest point, while maintaining tension in their hamstrings, and hold an isometric contraction while the researcher takes the angle of knee extension using a goniometer.

Figure 13. Nordic hamstring curl with the glute ham developer (youtube.com, 2018).

5.2.4. Statistical Analysis

The scores of the eccentric hamstring strength tests were compared between players who had hamstring injuries and players who did not suffer hamstring injuries. It was highlighted to the players that the lower scores were an indication of higher eccentric hamstring strength. The scores were compared via a two by three repeated measures ANOVA. All data were presented as mean ± standard deviation with $P < 0.05$ indicating significant difference.

The difference between the acute: chronic workload ratio between injured players and uninjured players were also analysed. Data from workload were taken from the season training load data used in study 1. The training load data analysed were the total distance covered, high-speed distance covered and the New Body Load. Acute workload was calculated as the average of the total workload from 7 days. Chronic workload was calculated as the average of the total workload from 28 days. The workload days chosen were 7 days and 28 days prior to a hamstring strain injury suffered by the group of injured players. The acute: chronic ratio was calculated as the acute workload divided by the chronic workload. An independent paired samples t-test was used to compare the acute: chronic workload ratio of the injured players against the uninjured players.

5.3. Results

5.3.1. Change in Nordic angle over the course of the season

As shown in Figure 14, there is no significant change in the Nordic hamstring curl angle over the course of the season (F (10, 118) = 1.183, p = 0.309).

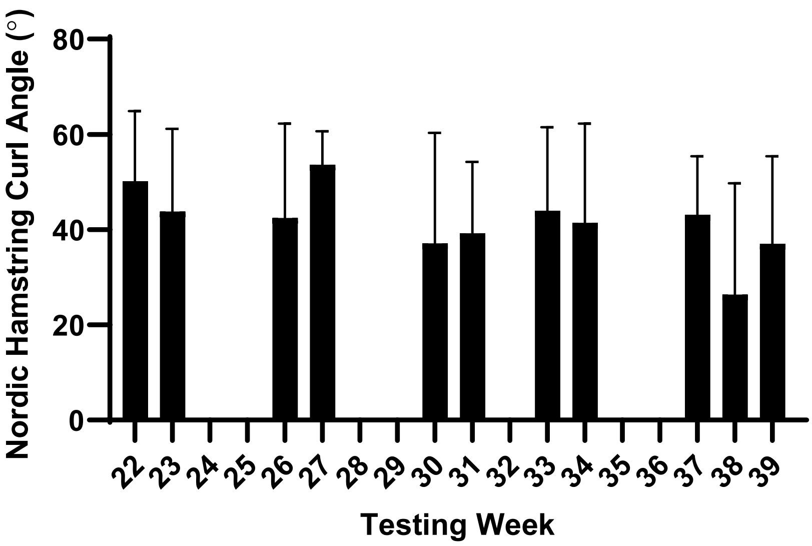


Figure 14: Change in Nordic hamstring curl angle (°) over the course of the season.

5.3.2. Difference between absolute Nordic angle between injured and non-injured players

From Figure 15, there were no statistical differences in the Nordic scores between the groups of players who had sustained hamstring injuries in the season and those who did not, F (2,16) = 1.303, p = 0.299.

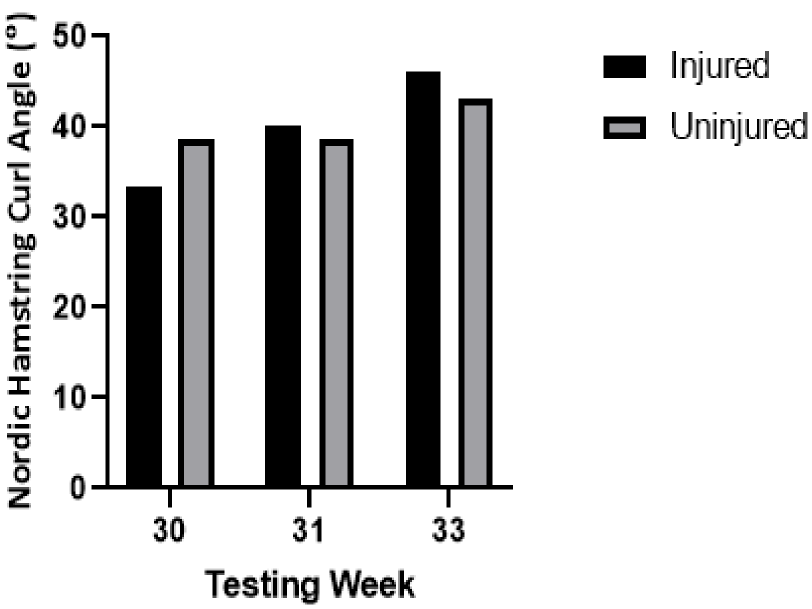


Figure 15: Comparison between the absolute Nordic angles between players who had sustained hamstring injuries and those who did not.

5.3.2. Acute: chronic workload ratios of injured players against non-injured players

As shown in Figure 16A, there is no significant difference in acute chronic ratio to injury incidence between players who had sustained hamstring injuries during the season and those who did not, t (14) = 0.729, p = 0.478. Similarly, Figure 16B shows that there is no significant difference in the high-speed distance ratio acute chronic ratio to injury incidence between players who had sustained hamstring injuries during the season and those who did not, t (14) = 1.082, p = 0.297. Figure 16C presents the New Body Load acute: chronic ratio between players who had sustained hamstring injuries during the season and those who did not had no significant difference in the acute chronic ratio to injury incidence t (14) = -1.04, p = 0.316.

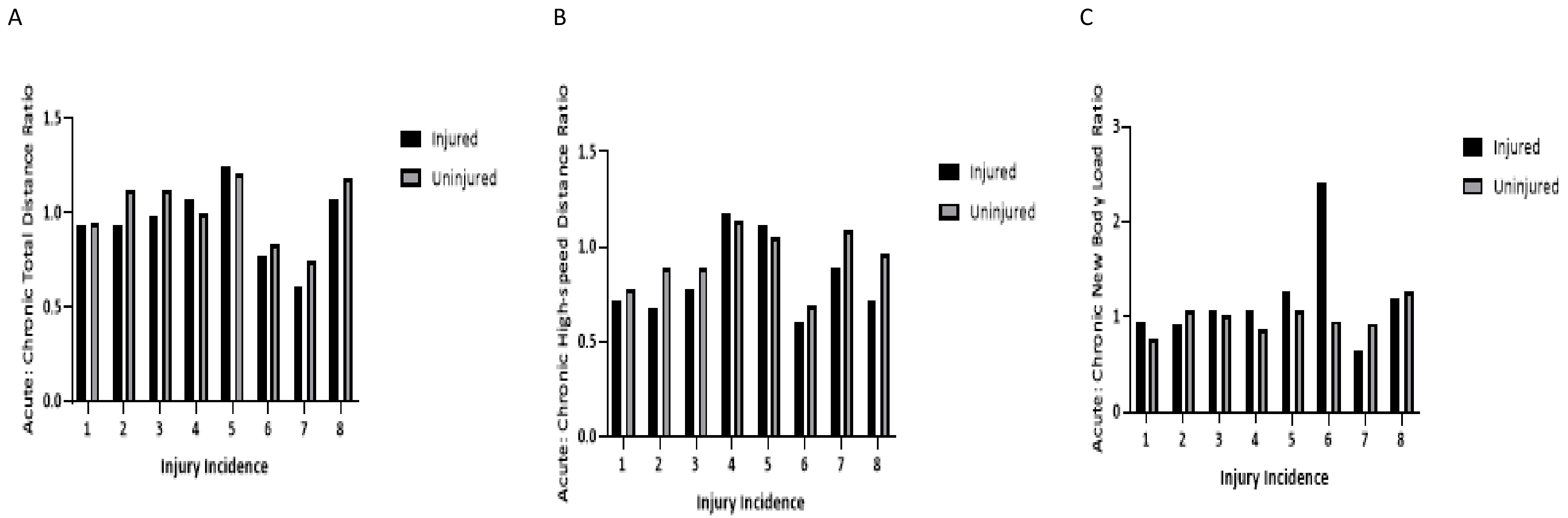


Figure 16. Comparison of acute: chronic workload ratios of injured players against non-injured players. A: Acute: chronic total distance ratio. B: Acute: chronic high-speed distance ratio. C: Acute: chronic New Body Load ratio.

5.3.3. Change in Nordic Performances and Change in Training Load

Figure 17 shows that the change in total distance does not correlate with the change in Nordic performance (r = 0.248, p = 0.097). The change in high-speed distance covered does not correlate with the change in Nordic performance (r = 0.012, p = 0.939). The change in New Body Load does not correlate with the change in Nordic performance (r = 0.176, p = 0.242).

A B C

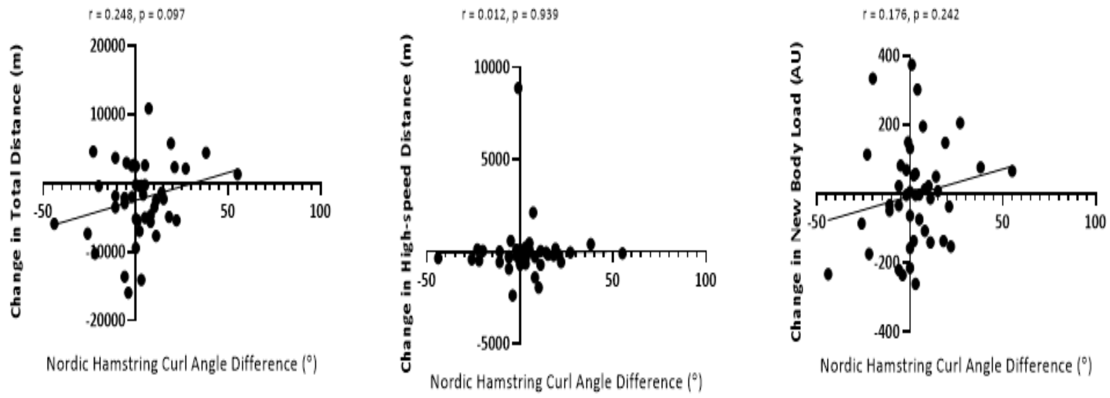


Figure 17. Change in training load and change in Nordic angle. A: Change in total distance covered. B: Change in high-speed distance covered. C: Change in New Body Load accumulated.

5.4. Discussion

The aim of the study was to evaluate eccentric hamstring strength and injury occurrence in relation to training load data throughout the competitive season. Results of the study demonstrate that the accumulation of the 7-day training load microcycle does not affect hamstring strength of the players, and there were no differences between the eccentric hamstring strength between players who sustained hamstring injuries when compared to those without hamstring injuries. As such $H1_0$ can be rejected. Moreover, results show that there were no significant differences between the acute: chronic workload between injured players and non-injured players, indicating $H2_0$ can be rejected.

5.4.1 Difference between absolute Nordic angle between injured and non-injured players

The results of the current study contrasted a previous study conducted on Australian rules football where the strength of those that had suffered hamstring injuries were significantly lower than those of the uninjured group (Opar et al., 2015). It was also reported that there were no significant differences between the strength of the injured limb and the contralateral uninjured limb at any point in the study (Opar et al., 2015). The current study only had 6 players suffering hamstring injuries throughout the season, therefore making the results of the current study less reliable. Low levels of eccentric strength suggested that the hamstrings have reduced ability to decelerate the limb moving forward during the terminal swing phase which could result in injury (Chumanov et al., 2011). Previous study using the isokinetic dynamometry measures to predict hamstring strain injuries among Australian rules footballers reported tests to be unsuccessful in predicting hamstring strain injury incidences (Bennell et al., 1998). However, the participants in mentioned study were a mixture of professional and high-level amateur players (Bennell et al., 1998). This mixture in levels may not generalise the results of professional athletes. Another study that did not find any differences between hamstring strength of participants that injured their hamstrings and those that did not (Worrell et al., 1991). However, it was found that athletes who sustained hamstring injuries had less flexibility in their hamstrings than those who did not sustain hamstring injuries, suggesting assessing and improving hamstring flexibility is key to preventing hamstring injuries (Worrell et al., 1991). These studies utilise isokinetic dynamometers to assess the hamstring strength of their participants, while the current study utilises the Nordic hamstring curl as a test for eccentric hamstring strength. The break-point angle of the Nordic hamstring curl test, the angle where the subject can no longer resist the increasing gravitational moment during a Nordic hamstring lower, shares a common variance with the eccentric knee-flexor torque, suggesting the two to be related (Thomas et al., 2015). There was also a correlation between the peak concentric hamstring torque at 60°/s and 240°/s with the break-point angle (Sconce et al., 2015). The limitation to using the Nordic hamstring curl to assess eccentric hamstring strength is that it is a bilateral leg-strength exercise and hence does not isolate the bilateral differences in eccentric hamstring strength (Sconce et al., 2015).

5.4.2 Acute: chronic workload ratios of injured players against non-injured players

The lack of difference between the acute: chronic workload ratio of players who had sustained hamstring injuries and those who did not were in contrast to previous study reporting acute: chronic workload ratios to predict injury (Hulin et al., 2016b). The acute: chronic workload ratio had been used to highlight injury precursors by reflecting on the negative short-term effects of fatigue and positive long-term effects of fitness to workloads (Gabbett, 2016). Previous research had shown that acute: chronic workload internal and external markers illustrated a range of 0.8 to 1.3 is considered the 'sweet spot' while 1.5 was the 'danger zone' for injury occurrence (Blanch and Gabbett, 2016). A study among youth elite soccer players reported that injury risk increased when a higher acute workload was combined with a low chronic workload, while the risk of injury was lower when combined with a low chronic workload (Bowen et al., 2017).

Despite the strong associations between the acute: chronic workload and injury incidence, training loads were found to not exhibit an increased risk of injury (Fanchini et al., 2018). When the durations of the chronic workloads were manipulated, the acute: chronic workload ratios were high but were unable to accurately predict non-contact injuries (Fanchini et al., 2018). In the current study, the acute: chronic workload ratio of the uninjured players were similar to the ones of the injured players and were within the 0.8 to 1.3 'sweet spot'. The results of the current study are similar to that of a previous study that reported no significant changes in training load of players within weeks prior to their injuries (Lu et al., 2017). Increasing workloads gradually weekly and reducing 'spikes' in training loads were suggested to reduce the risk of injury (Gabbett, 2015). The lack of change in total distance covered in the weeks leading up to injury may have been influenced by planned sustained high training load prescription (Lu et al., 2017).

There are, however, some limitations to using the acute: chronic workload ratio to assess injury incidence. When assessing a player's locomotor profile, using a fixed speed threshold to define high-speed running zones may limit the sensitivity of the acute: chronic workload ratio with respect to high-speed running load (Malone et al., 2017). This is to take into account the subtle differences in sprinting intensity such as high (85 - 95% of maximal sprinting speed) and very high-speed running (> 95%) may have important implications to injury risk and individualisation (Malone et al., 2017). Hence, individualisation of high-speed running zones via using the players' maximal speed as reference is important in this regard (Bucheit, 2017). Besides, the lack of fitness testing done throughout the season in professional football makes defining the acute: chronic workload ratio difficult when monitoring players with varying and unknown fitness levels (example, acute: chronic ratio > 1.2 vs. > 1.5 vs. > 1.8) (Bucheit, 2017). Therefore, these difficulties are likely to limit the sensitivity of the acute: chronic workload ratio and consequently making it useless to this specific population (Bucheit, 2017).

5.4.3. Experimental Limitations

It should be highlighted in the current study that there was a lack of number of players suffering hamstring injuries to provide sufficient data. Additionally, the Nordic hamstring curl tests were performed sporadically over the course of the season, leaving with limited data for analysis. The Nordic hamstring curl tests were also done after training sessions where players are most likely fatigued. Besides, only long-term hamstring injuries were taken into account in this study, while hamstring injuries that did not cause absences from training and matches were not analysed. Age, body weight and previous injuries were not taken into account when conducting this study. The current study has a limitation where the data collected and analysed were done on a 'team level' basis instead of individual analysis of each player. It has been shown that strong associations may not predict injury (Pepe et al., 2004). Although associations such as odds ratio or relative risk can be useful to characterise the risk of a population, they are not predictive tools (Pepe et al., 2004). To determine the true use of a marker, the predictive validity and optimal cut-off value have to be assessed together with the association (Fawcett, 2006).

5.4.4. Practical Implications

More research is required with manipulation of the duration of the chronic workload period and utilisation of other GPS variables to further understand implications of acute and chronic workloads. In the current study, the use of acute: chronic workload ratio cannot predict the occurrence of hamstring injury incidence.

The use of Nordic hamstring curl test is a practical and inexpensive method to assess the eccentric strength of athletes especially during pre-season. Assessing and identifying potential weaknesses in the hamstrings will allow coaches and physiotherapists to help the players strengthen the hamstrings and reduce the risk of injury.

5.4.5. Conclusion

This study had found that acute: chronic workload ratios may not be used to predict non-contact injury incidences. Sports scientists have to be weary when using acute: chronic workload ratio when monitoring workload of players. The Nordic hamstring curl test can be used to assess the eccentric hamstring strength of athletes.

Chapter 6: General Discussion

6.1. Synthesis of Findings

The purpose of the present thesis was to investigate the effects of training load on soccer match performance, and injury incidence. This chapter will provide a conceptual and theoretical interpretation of the results obtained from the present thesis. An evaluation of the original aims and objectives will be conducted prior to reviewing the outcomes of the experimental studies.

The first experimental study in the present thesis highlights the strategies employed by a professional soccer club to monitor their players' workload via GPS monitoring throughout the entire competitive season. Previously, research has tended to investigate specific periods within the season associated with pre-season, or periods of time with intensive training loads (Los Arcos et al., 2014, Impellizzeri et al., 2004 and Brink et al., 2010). The first experimental study documented in Chapter 3 aimed to quantify the training periodisation practices used by an English League 1 professional soccer club. In order to do this, external training load data were collected via GPS and analysed throughout a competitive season. No significant differences were observed in the New Body Load accumulated when comparing the different stages and phases of the season. However, there were significant differences in the total distance covered and the high-speed distance covered. The high-speed distance covered was found to peak at stages of the season with high fixture congestion. This suggests that there is not a clear periodisation plan especially during periods of high fixture congestion where the workload during sessions were supposed to be reduced to promote recovery for the upcoming matches. These results were similar to a previous study on an elite professional soccer team where the analysis showed limited variation in the training load variables across the majority of the in-season mesocycles (Malone et al., 2015a). They had suggested that the limited variation in training load was because of the time restraints of elite level soccer competition (Malone et al., 2015a). Similarly, the soccer club in the current research was also limited in time as they had a large number of matches to play in a fixed amount of time, sometimes as many as those of an elite club playing in continental competitions (Carling et al., 2015). The high fixture congestion in short periods of the competitive season could potentially induce residual fatigue and also increase the risk of injury among the players (Dupont et al., 2010). Players require 72 to 120 hours of recovery period for them to achieve pre-match performance in physical capabilities (Ispirlidis et al., 2008).

The study also sought to investigate strategies of managing the training load of the players during periods of fixture congestion, which is a common occurrence during the season. Training load from training sessions alone and matches alone were analysed to identify differences in total weekly training load when competitive fixtures were scheduled differently. Significant differences were found in the total distances covered, high-speed distances covered and accumulated New Body Load from training sessions. Similar results were observed in a previous study where the training load was significantly reduced on the day before the match (Malone et al., 2015a). It was suggested that the coaches attempted to limit fatigue among the players leading to the match via this method (Malone et al., 2015a). There were no significant differences observed in total distance covered, high-speed distance covered and New Body Load accumulated from individual matches. When workload from training sessions and matches together, no significant differences were observed. These results suggest that coaches had manipulated the workload of training sessions so that players have sufficient recovery time for the following match. Previous study had also found that periods of intensified training can lead to reduction in performances in fitness tests, but significant improvements after a tapering period (Coutts and Reapburn, 2008). It was inferred that the players were in an overreached state after the period of intensified training (Coutts and Reapburn, 2008). This highlights the importance of a taper to prevent the risk of players from overreaching. The tapering of training sessions would allow for the players to maintain their physical performance in matches as shown in the current study. The tapering approach could be done by reducing training session frequency, training volume and intensity

(Wenger et al., 2008). Similar to a previous study, tapering via a reduction in training volume was mostly applied in the current study (Bousquet et al., 2007). This is because decreasing the training load via reduction in training frequency had resulted in a lack of improvement in sporting performance (Bousquet et al., 2007). By adhering to the tapering approach, the running performance of the players in the matches analysed when comparing between 1 match per week versus 2 matches were similar. The results were similar to a previous study where the high-speed distance covered during matches separated by 4 days did not change (Dupont et al., 2010).

By understanding the methods to manage training load during these periods (such as reducing volume and/or intensity), players will be able to recover appropriately and therefore perform to their optimum during matches, regardless of the frequency of matches in a week.

The results from the quantification of the training load data across the season appeared to contradict the results of the training load data of the weeks in preparation for 1 match versus 2 matches. While it was mentioned that there was a lack of manipulation in the training load over the course of the season, training load data of the weeks in preparation for 1 match versus 2 matches did show manipulation in training load to prepare for the respective matches. This contradiction may be because of the different analytical methods to detect changes in the training load throughout the season and comparing training load of selected individual weeks with 1 or 2 matches. The data may have been skewed because the mesocycles have a mixture of 1 and 2 matches which are not evenly distributed. Hence, coaches and sport scientists should include both longer term trends and short 7-day microcycle data in their analysis of training load.

A subanalysis in this study was the assessment of neuromuscular fatigue of the players via CMJ tests throughout the season. Players may experience fatigue from constantly training and playing matches throughout the season, although the current study failed to find any evidence of this. Previous research has suggested that the ability to generate power of the players should return to baseline levels after 72 hours of recovery (Ascensao et al., 2008 and Rollo et al., 2014). There were also no significant differences observed between jumps completed after a 7-day microcycle. This data suggested that the players were able to tolerate the workloads from a 7-day microcycle consisting of training sessions and typically one match. As the CMJ tests were performed on a weekly basis, the players may have already recovered by the next test (Ascensao et al., 2008 and Rollo et al., 2014). The results may also suggest that the countermovement jump test might not be an accurate and/or sensitive enough assessment of neuromuscular fatigue. The change in the jump height of current study is approximately -1.0%, which is lower than the test-retest values of such procedures (Malone et al., 2015b). Hence, it is difficult to determine whether the changes in neuromuscular function measured by the countermovement jump has an effect on the players' match performance. Indeed, this lack of sensitivity has also been suggested by Freitas et al. (2014), where there was also no change in height from the countermovement jump tests among volleyball players despite varying the total weekly training load. The lack of change in jump height difference from the countermovement jump tests were possibly due to the methodology where tests were conducted after a short period of time (one test after a 7-day microcycle). Therefore, coaches and sports scientist need to carefully evaluate the validity and/or reliability of CMJ to assess neuromuscular fatigue. Future research should include a comparison between the jump height difference between jump tests conducted at the beginning of the season or during pre-season and subsequent tests over the course of the competitive season. By doing so, sport scientists can determine the level, if any, of fatigue the player experiences over the course of the season and intervene when necessary. It also serves as an indicator whether the tapering strategies are effective on the players.

Understanding external training load may be useful as well to prevent players from succumbing to injuries, especially non-contact injuries. There is much debate on whether training load can be used to predict non-contact injuries among players (Hulin et al., 2016b and Fanchini et al., 2018). The second experimental study highlights the incorporation of Nordic eccentric hamstring curl test as an on-field test to assess eccentric hamstring strength together with training load of the players as tools to monitor them for potential injuries.

Players performed the Nordic eccentric hamstring curl test and their scores were analysed in relation to hamstring injury incidence. Their training load was derived as acute and chronic workloads using the acute: chronic workload ratio (Hulin et al., 2014). No significant differences were found between the scores of the Nordic eccentric hamstring curl test and the hamstring injury incidence. No significant differences were observed as well between the acute: chronic workload ratios and the hamstring injury incidence. These results suggest that the eccentric hamstring strength may not be a factor on the occurrence of hamstring injuries and the acute: chronic workload ratio may not predict non-contact soft tissue injuries. Results of the current study therefore support previous research which failed to find a relationship between high training load and an increase of the risk of injury (Fanchini et al., 2018). Nevertheless, other research has suggested that acute: chronic workload ratios can predict injury (Hulin et al., 2016b). Specifically, acute: chronic workload ratios in the range of 0.8 to 1.3 have been suggested to be the 'sweet spot' for training, with ratios > 1.5 in a 'danger zone' associated with increased risk of injury occurrence (Blanch and Gabbett, 2016; Fanchini et al., 2018). Given these contradictory findings, clearly more research work is required to establish whether the acute: chronic workload ratio is able to predict non-contact injury incidence. There are also limitations for using acute: chronic workload ratios to predict injury incidence as it does not account for match to match variability, or different locomotor profiles of the player within the fixed training load thresholds used (Buchheit, 2017).

The use of training load monitoring should therefore most likely be suggested as a monitoring tool rather than a definitive method to prevent non-contact injury.

6.2. Practical Implications

A major finding in the first experimental study was the reduction of training load during weeks with 2 matches in a single week. The coaches did so by reducing the time period of training sessions one day before matches. Other methods to taper training utilised by the coaches included reducing the frequency of training sessions in a week and lowering the intensity of training sessions. By doing so, the players will have the required stimulus to be ready for matches while adequate recovery.

From the findings of the current studies, monitoring the training load of the players is an important aspect to maintaining the team's performance at a high level and reducing the risk of injury among the players. However, more emphasis has to go into individualising the intensity thresholds for each player, rather than relying on the absolute thresholds set. By doing so, players will be able to train at the appropriate intensities in preparation for matches. Sports scientists and coaches also have to be able to manipulate and periodise training sessions according to the fixture distributions in the season. They must utilise the training load monitoring system to reduce and taper training sessions without compromising the intensity, especially during periods of fixture congestion. This is to reduce the risk of injury and maintain match performance.

6.3. Thesis Limitations

A few limitations can be found throughout the two studies. In the first study, the sample size was reduced markedly as the season progressed. This was due to some players sustaining long-term injuries and leaving the club during the transfer period, resulting in incomplete data collection from these players. Next, analyses of the training load from matches included those from unused substitutes. The data from these players include the warm-up and runs at the end of the match (specifically for substitutes), but these data alone does not reflect the intensity of the actual match. Another limitation to this study was that the training load of all the players were analysed as a collective group, rather than by position. Consequently, there was a high variability in the data as players in different positions perform different amounts of high-intensity movements (Carling et al., 2008). Moreover, the data from the countermovement jump tests were sporadic and inconsistent as some players were unwilling to perform jumps either out of fear of injuring themselves or under the claim of being “too tired” from the match.

In the second study, the lack of players suffering from hamstring injuries over the season was a limitation as there was insufficient data to study injury incidences. Furthermore, hamstring injuries that did not cause absences from training or matches were not taken into account in this study. Next, the Nordic hamstring curl tests were also completed sporadically, resulting in limited data for analysis. They were also done after training sessions when players were most likely fatigued. Besides, age, body weight and history of previous injuries were not taken into account in the current study. The current study has a limitation where the data collected and analysed were done on a ‘team level’ basis instead of individual analysis of each player. It has been shown that strong associations may not predict injury (Pepe et al., 2004). Although associations such as odds ratio or relative risk can be useful to characterise the risk of a population, they are not predictive tools (Pepe et al., 2004). To determine the true use of a marker, the predictive validity and optimal cut-off value have to be assessed together with the association (Fawcett, 2006). In the current study, there were no differences between the eccentric hamstring strength of the players who had not injured their hamstrings and those who had. As the data collected for this study was rather sporadic, blaming the hamstring injury on weak hamstring eccentric strength was difficult. In addition, the isometric Nordic hamstring curl test may not have challenged players as much when done with only their bodyweight. Therefore, future research can perform a similar test where the players have to hold a predetermined weight across their chest as they perform the isometric hamstring curl.

6.4. Future Research Questions

From the current study, a few research questions can be further generated for the near future. Some of the areas that can be further researched are the comparison of training periodisation and tapering practices employed by different professional soccer clubs of different levels throughout a competitive season. Clubs competing at an elite level will have different strategies to periodise training as they take into account competing in intercontinental and domestic competitions. Involvement in intercontinental competitions will involve more travelling, which may disrupt training plans and the players’ ability to recover. The next research question to investigate could be to quantify the player’s technical ability together with running performance and their effects on match performance. Very few studies had studied the influence of technical abilities of the players (Zeederberg et al.,1996, McGregor et al., 1999 and Burgomaster et al., 2005). By investigating the players’ technical abilities during matches, sports scientists can determine their impact on the outcome of matches. The reliability and validity of isometric Nordic hamstring curl test to measure eccentric hamstring strength could also be investigated in the future. It is a convenient and simple method to test for eccentric hamstring strength, there are limited studies regarding its validity and reliability. Researching these questions would help sports scientists further understand the effectiveness of the workload monitoring to improve sporting performance and prevent injury among elite soccer players.

6.5. Conclusion

The aims of this thesis were to investigate the relationship between training load monitoring and its effects on football match performance. These aims have been fulfilled through the completion of the objectives set out in Chapter 2. The use of GPS devices is now widely used in professional team sports. The training periodisation strategies were found to fluctuate as the season progresses because of the periods of the season with high fixture count. Coaches and sports scientists have strived to accommodate this by manipulating the players' workload in training to promote recovery in preparation for the upcoming match. It was also found that the neuromuscular function status of the players remained constant for parts of the season. This finding that the training periodisation had maintained their fitness levels more than improving their physical capabilities during certain periods of the season. It was also revealed that training load monitoring may not necessarily predict non-contact injury occurrences. Eccentric hamstring strength tests were also not ideal methods to predict hamstring injury occurrences despite a correlation of eccentric hamstring strength with hamstring strain injuries. In general, these methods are suitable precautionary measures to identify those at risk more than a definitive method to predict as hamstring strain injuries have multiple factors to it that cannot be controlled.

Chapter 7: Reference List

Aagaard, P., Simonsen, E.B., Magnusson, S.P., Larsson, B. and Dyhre-Poulsen, P. (1998). A new concept for isokinetic hamstring: quadriceps muscle strength ratio. *The American journal of sports medicine*, *26*(2), pp.231-237.

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. *Journal of sports sciences, 27*(9), pp.893-898.

Achten, J. and Jeukendrup, A.E. (2003). Heart rate monitoring. *Sports medicine*, *33*(7), pp.517-538.

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

Akenhead, R. and Nassis, G.P. (2016). Training load and player monitoring in high-level football: current practice and perceptions. *International journal of sports physiology and performance*, *11*(5), pp.587-593.

Akubat, I. and Abt, G. (2011). Intermittent exercise alters the heart rate–blood lactate relationship used for calculating the training impulse (TRIMP) in team sport players. *Journal of science and medicine in sport*, *14*(3), pp.249-253.

Al Haddad, H., Simpson, B. and Buchheit, M. (2015). Monitoring Changes in Jump and Sprint Performance: Best or Average Values? *International Journal of Sports Physiology & Performance* *10*(7), pp.931-934.

Alexiou, H. and Coutts, A.J. (2008). A comparison of methods used for quantifying internal training load in women soccer players. *International journal of sports physiology and performance*, *3*(3), pp.320-330.

Allen, T.J., Leung, M. and Proske, U. (2010). The effect of fatigue from exercise on human limb position sense. *The Journal of physiology*, *588*(8), pp.1369-1377.

Anderson, L., Orme, P., Di Michele, R., Close, G.L., Morgans, R., Drust, B. and Morton, J.P. (2016). Quantification of training load during one-, two-and three-game week schedules in professional soccer players from the English Premier League: implications for carbohydrate periodisation. *Journal of sports sciences*, *34*(13), pp.1250-1259.

Anderson, L., Triplett-Mcbride, T., Foster, C., Doberstein, S. and Brice, G. (2003). Impact of training patterns on incidence of illness and injury during a women's collegiate basketball season. *The Journal of Strength & Conditioning Research*, *17*(4), pp.734-738.

Andersson, H., Ekblom, B. and Krustrup, P, (2008). Elite football on artificial turf versus natural grass: movement patterns, technical standards, and player impressions. *Journal of sports sciences*, *26*(2), pp.113-122.

Andersson, H., Krustrup, P. and Mohr, M. (2007). Differences in movement pattern, heart rate and fatigue development in international versus national league matches of Swedish and Danish elite female soccer players. *Journal of Sports Science and Medicine*, *6*(10), pp.106-110.

Andersson, H.Å., Randers, M.B., Heiner-Møller, A., Krustrup, P. and Mohr, M. (2010). Elite female soccer players perform more high-intensity running when playing in international games compared with domestic league games. *The Journal of Strength & Conditioning Research, 24*(4), pp.912-919.

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. *Medicine & Science in Sports & Exercise*, *40*(2), pp.372-380.

Andrew, G.M., Guzman, C.A. and Becklake, M.R. (1966). Effect of athletic training on exercise cardiac output. *Journal of applied physiology, 21*(2), pp.603-608.

Arnason, A., Andersen, T.E., Holme, I., Engebretsen, L. and Bahr, R. (2008). Prevention of hamstring strains in elite soccer: an intervention study. *Scandinavian journal of medicine & science in sports*, *18*(1), pp.40-48.

Arnason, A., Sigurdsson, S.B., Gudmundsson, A., Holme, I., Engebretsen, L. and Bahr, R. (2004). Risk factors for injuries in football. *The American journal of sports medicine*, *32*(1), pp.5-16.

Arnason, A., Sigurdsson, S.B., Gudmundsson, A., Holme, I., Engebretsen, L. and Bahr, R. (2004). Physical fitness, injuries, and team performance in soccer. *Medicine & Science in Sports & Exercise*, *36*(2), pp.278-285.

Arteaga, R., Dorado, C., Chavarren, J. and Calbet, J.A.L. (2000). Reliability of jumping performance in active men and women under different stretch loading conditions. *Journal of Sports Medicine and Physical Fitness*, *40*(1), pp.26-34.

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. *Clinical biochemistry*, *41*(10-11), pp.841-851.

Askling, C.M., Tengvar, M., Saartok, T. and Thorstensson, A. (2007). Acute first-time hamstring strains during high-speed running: a longitudinal study including clinical and magnetic resonance imaging findings. *The American journal of sports medicine*, *35*(2), pp.197-206.

Aughey, R.J. (2011). Applications of GPS technologies to field sports. *International journal of sports physiology and performance, 6*(3), pp.295-310.

Baechle, T.R. and Earle, R.W. (2008). *Essentials of strength training and conditioning*. Human kinetics.

Bahr, R. (2016). Why screening tests to predict injury do not work—and probably never will…: a critical review. *Br J Sports Med*, *50*(13), pp.776-780.

Balsalobre-Fernández, C., Tejero-González, C.M. and del Campo-Vecino, J. (2014). Relationships between training load, salivary cortisol responses and performance during season training in middle and long distance runners. *PloS one*, *9*(8), 1-8.

Bangsbo, J. (1994). The physiology of soccer--with special reference to intense intermittent exercise. *Acta Physiologica Scandinavica. Supplementum*, *619*, pp.1-155.

Bangsbo, J. (2014). Physiological demands of football. *Sports Science Exchange*, *27*(125), pp.1-6.

Bangsbo, J., Gollnick, P.D., Graham, T.E. and Saltin, B. (1991). Substrates for muscle glycogen synthesis in recovery from intense exercise in man. *The Journal of physiology*, *434*(1), pp.423-440.

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

Bangsbo, J., Nørregaard, L. and Thorsoe, F. (1991). Activity profile of competition soccer. *Canadian journal of sport sciences, 16*(2), pp.110-116.

Banister, E.W. and Calvert, T.W. (1980). Planning for future performance: implications for long term training. *Canadian journal of applied sport sciences. Journal canadien des sciences appliquees au sport*, *5*(3), pp.170-176.

Banister, E.W., Calvert, T.W., Savage, M.V. and Bach, T. (1975). A systems model of training for athletic performance. *Aust J Sports Med*, *7*(3), pp.57-61.

Banister, E.W., Good, P., Holman, G. and Hamilton, C.L. (1986). Modeling the training response in athletes. *Sport and elite performers*, *3*, pp.7-23.

Bannister, E.W. (1991). Modelling elite athletic performance. *Physiological Testing of Elite Athletes. Champaign (IL): Human Kinetics*, pp.403-24.

Barros, R.M., Misuta, M.S., Menezes, R.P., Figueroa, P.J., Moura, F.A., Cunha, S.A., Anido, R. and Leite, N.J. (2007). Analysis of the distances covered by first division Brazilian soccer players obtained with an automatic tracking method. *Journal of sports science & medicine, 6*(2), p.233-242.

Bengtsson, H., Ekstrand, J. and Hägglund, M. (2013). Muscle injury rates in professional football increase with fixture congestion: an 11-year follow-up of the UEFA Champions League injury study. *Br J Sports Med*, *47*(12), pp.743-747.

Bennell, K., Tully, E. and Harvey, N. (1999). Does the toe-touch test predict hamstring injury in Australian Rules footballers? *Australian Journal of Physiotherapy*, *45*(2), pp.103-109.

Bennell, K., Wajswelner, H., Lew, P., Schall-Riaucour, A., Leslie, S., Plant, D. and Cirone, J. (1998). Isokinetic strength testing does not predict hamstring injury in Australian Rules footballers. *British journal of sports medicine*, *32*(4), pp.309-314.

Bigland-Ritchie, B., Johansson, R., Lippold, O.C. and Woods, J.J. (1983). Contractile speed and EMG changes during fatigue of sustained maximal voluntary contractions. *Journal of neurophysiology*, *50*(1), pp.313-324.

Bigland-Ritchie, B. (1981). EMG/force relations and fatigue of human voluntary contractions. *Exercise and sport sciences reviews*, *9*(1), pp.75-118.

Blanch, P. and Gabbett, T.J. (2016). Has the athlete trained enough to return to play safely? The acute: chronic workload ratio permits clinicians to quantify a player's risk of subsequent injury. *Br J Sports Med*, *50*(8), pp.471-475.

Blankenbaker, D.G. and Tuite, M.J. (2010). Temporal changes of muscle injury. In *Seminars in musculoskeletal radiology*, *14*(2), pp. 176-193.

Bompa, T.O. and Buzzichelli, C. (2018). *Periodization-: theory and methodology of training*. Human Kinetics.

Borg, G. (1998). *Borg's perceived exertion and pain scales*. Human kinetics.

Borg, G., Hassmén, P. and Lagerström, M. (1987). Perceived exertion related to heart rate and blood lactate during arm and leg exercise. *European journal of applied physiology and occupational physiology, 56*(6), pp.679-685.

Borg, G., Ljunggren, G. and Ceci, R. (1985). The increase of perceived exertion, aches and pain in the legs, heart rate and blood lactate during exercise on a bicycle ergometer. *European journal of applied physiology and occupational physiology, 54*(4), pp.343-349.

Borg, G.A. (1973). Perceived exertion: a note on "history" and methods. *Medicine and science in sports, 5*(2), pp.90-93.

Borresen, J. and Lambert, M.I. (2008). Autonomic control of heart rate during and after exercise. *Sports medicine, 38*(8), pp.633-646.

Borresen, J. and Lambert, M.I. (2009). The quantification of training load, the training response and the effect on performance. *Sports medicine*, *39*(9), pp.779-795.

Bosquet, L., Merkari, S., Arvisais, D. and Aubert, A.E. (2008). Is heart rate a convenient tool to monitor over-reaching? A systematic review of the literature. *British journal of sports medicine, 42*(9), pp.709-714.

Bosquet, L., Montpetit, J., Arvisais, D. and Mujika, I. (2007). Effects of tapering on performance: a meta-analysis. *Medicine & Science in Sports & Exercise*, *39*(8), pp.1358-1365.

Bouchard, C. and Rankinen, T. (2001). Individual differences in response to regular physical activity. *Medicine and science in sports and exercise*, *33*(6), pp.446-451.

Bourdon, P.C., Cardinale, M., Murray, A., Gastin, P., Kellmann, M., Varley, M.C., Gabbett, T.J., Coutts, A.J., Burgess, D.J., Gregson, W. and Cable, N.T. (2017). Monitoring athlete training loads: consensus statement. *International journal of sports physiology and performance*, *12*(s2), pp.161-170.

Bowen, L., Gross, A.S., Gimpel, M., 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), pp.452–459.

Boyas, S. and Guével, A. (2011). Neuromuscular fatigue in healthy muscle: underlying factors and adaptation mechanisms. *Annals of physical and rehabilitation medicine*, *54*(2), pp.88-108.

Boyd, L. and Ball, K. (2008). A Profile of Training and Match Demands. *Proceedings of Football Australasia*, 3, pp. 29.

Bradley, P.S. and Portas, M.D. (2007). The relationship between preseason range of motion and muscle strain injury in elite soccer players. *Journal of Strength and Conditioning Research*, *21*(4), pp.1155-1159.

Bradley, P.S., Carling, C., Diaz, A.G., Hood, P., Barnes, C., Ade, J., Boddy, M., Krustrup, P. and Mohr, M. (2013). Match performance and physical capacity of players in the top three competitive standards of English professional soccer. *Human movement science*, *32*(4), pp.808-821.

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), pp.2343-2351.

Brink, M.S., Nederhof, E., Visscher, C., Schmikli, S.L. and Lemmink, K.A. (2010). Monitoring load, recovery, and performance in young elite soccer players. *The Journal of Strength & Conditioning Research*, *24*(3), pp.597-603.

Brooks, J.H., Fuller, C.W., Kemp, S.P. and Reddin, D.B. (2006). Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. *The American journal of sports medicine*, *34*(8), pp.1297-1306.

Brown, L.E. and Greenwood, M. (2005). Periodization essentials and innovations in resistance training protocols. *Strength and Conditioning Journal*, *24*(4), pp.80-85.

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. *Frontiers in physiology*, *8*, pp.831. https://doi.org/10.3389/fphys.2017.00831

Brulé, P., Carling, C., David, A., Da Graça, F., Giorgi, J.M., Villet, D. and Garberino, J. (1998). AMISCO: the development of a computerised match analysis system to automatically track the movements of soccer players. In *Proceedings of the IV World Congress of Notational Analysis of Sport, University of Porto,* pp. 22-25.

Buchheit, M. (2017). Applying the acute: chronic workload ratio in elite football: worth the effort? *Br J Sports Med. 51*(18), pp.1325–1327.

Buchheit, M., Chivot, A., Parouty, J., Mercier, D., Al Haddad, H., Laursen, P.B. and Ahmaidi, S. (2010). Monitoring endurance running performance using cardiac parasympathetic function*. European journal of applied physiology, 108*(6), pp.1153-1167.

Buchheit, M. and Gindre, C. (2006). Cardiac parasympathetic regulation: respective associations with cardiorespiratory fitness and training load*. American Journal of Physiology-Heart and Circulatory Physiology, 291*(1), pp.451-458.

Buchheit, M., Millet, G.P., Parisy, A., Pourchez, S., Laursen, P.B. and Ahmaidi, S. (2008). Supramaximal training and postexercise parasympathetic reactivation in adolescents. *Medicine and science in sports and exercise, 40*(2), pp.362-371.

Buford, T.W., Rossi, S.J., Smith, D.B. and Warren, A.J. (2007). A comparison of periodization models during nine weeks with equated volume and intensity for strength. *The Journal of Strength & Conditioning Research*, *21*(4), pp.1245-1250.

Burgess, D.J. (2017). The research doesn’t always apply: practical solutions to evidence-based training-load monitoring in elite team sports. *International journal of sports physiology and performance*, *12*(s2), pp.136-141.

Burgess, D.J., Naughton, G. and Norton, K.I. (2006). Profile of movement demands of national football players in Australia. *Journal of Science and Medicine in Sport, 9*(4), pp.334-341.

Burgomaster, K.A., Hughes, S.C., Heigenhauser, G.J., Bradwell, S.N. and Gibala, M.J. (2005). Six sessions of sprint interval training increases muscle oxidative potential and cycle endurance capacity in humans. *Journal of applied physiology*, *98*(6), pp.1985-1990.

Burkett, L. (1970). Causative factors in hamstring strains. *Medicine and science in sports*, *2*(1), pp.39-42.

Butterfield, T.A. (2010). Eccentric exercise in vivo: strain-induced muscle damage and adaptation in a stable system. *Exercise and sport sciences reviews*, *38*(2), pp.51-60.

Cabri, J.M.H. and Clarys, J.P. (1991). Isokinetic exercise in rehabilitation. *Applied ergonomics*, *22*(5), pp.295-298.

Calvert, T.W., Banister, E.W., Savage, M.V. and Bach, T. (1976). A systems model of the effects of training on physical performance. *IEEE Transactions on systems, man, and cybernetics*, (2), pp.94-102.

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

Carling, C., Orhant, E. and LeGall, F. (2010). Match injuries in professional soccer: inter-seasonal variation and effects of competition type, match congestion and positional role. *International journal of sports medicine*, *31*(04), pp.271-276.

Carling, C., Reilly, T. and Williams, A.M. (2007). *Handbook of soccer match analysis: A systematic approach to improving performance.* Routledge.

Carling, C. (2001). Getting the most out of football video and match analysis. *Insight FA Coaches Association Journal, 5*(3), pp.16-17.

Carling, C. (2011). Influence of opposition team formation on physical and skill-related performance in a professional soccer team. *European Journal of Sport Science*, *11*(3), pp.155-164.

Carling, C. and Bloomfield, J. (2010). The effect of an early dismissal on player work-rate in a professional soccer match. *Journal of Science and Medicine in Sport*, *13*(1), pp.126-128.

Carling, C. and Dupont, G. (2011). Are declines in physical performance associated with a reduction in skill-related performance during professional soccer match-play? *Journal of sports sciences*, *29*(1), pp.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 Medicine*, *45*(5), pp.605-613.

Carling, C., Le Gall, F. and Dupont, G. (2012). Are physical performance and injury risk in a professional soccer team in match-play affected over a prolonged period of fixture congestion? *International journal of sports medicine*, *33*(01), pp.36-42.

Castagna, C., Impellizzeri, F.M., Chaouachi, A. and Manzi, V. (2013). Preseason variations in aerobic fitness and performance in elite-standard soccer players: a team study. *The Journal of Strength & Conditioning Research*, *27*(11), pp.2959-2965.

Castellano, J. and Casamichana, D. (2010). Heart rate and motion analysis by GPS in beach soccer. *Journal of sports science & medicine*, *9*(1), pp.98-103.

Catapult Products. Retrieved from https://www.catapultsports.com/products/gpsports-evo?redirect=true. Last accessed 15/08/2018.

Chad, N. (2010). An approach to the periodisation of training during the in-season for team sports. *Prof Strength Cond*, *18*, pp.5-10.

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. *Journal of sports sciences*, *20*(11), pp.873-899.

Child, R.B., Wilkinson, D.M. and Fallowfield, J.L. (2000). Effects of a training taper on tissue damage indices, serum antioxidant capacity and half-marathon running performance. *International journal of sports medicine*, *21*(05), pp.325-331.

Chumanov, E.S., Heiderscheit, B.C. and Thelen, D.G. (2011). Hamstring musculotendon dynamics during stance and swing phases of high-speed running. *Medicine and science in sports and exercise*, *43*(3), pp.525-532.

Clanton, T.O. and Coupe, K.J. (1998). Hamstring strains in athletes: diagnosis and treatment. *JAAOS-Journal of the American Academy of Orthopaedic Surgeons*, *6*(4), pp.237-248.

Clark, R., Bryant, A., Culgan, J.P. and Hartley, B. (2005). The effects of eccentric hamstring strength training on dynamic jumping performance and isokinetic strength parameters: a pilot study on the implications for the prevention of hamstring injuries. *Physical Therapy in Sport*, *6*(2), pp.67-73.

Claudino, J.G., Cronin, J., Mezêncio, B., McMaster, D.T., McGuigan, M., Tricoli, V., Amadio, A.C. and Serrão, J.C. (2017). The countermovement jump to monitor neuromuscular status: A meta-analysis. *Journal of science and medicine in sport*, *20*(4), pp.397-402.

Claudino, J.G., Cronin, J.B., Mezêncio, B., Pinho, J.P., Pereira, C., Mochizuki, L., Amadio, A.C. and Serrão, J.C. (2016). Autoregulating jump performance to induce functional overreaching. *Journal of strength and conditioning research*, *30*(8), pp.2242-2249.

Coffey, V.G. and Hawley, J.A. (2007). The molecular bases of training adaptation. *Sports medicine*, *37*(9), pp.737-763.

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), pp.2244-2252.

Coombs, R. and Garbutt, G., (2002). Developments in the use of the hamstring/quadriceps ratio for the assessment of muscle balance. *Journal of sports science & medicine*, *1*(3), p.56 – 62

Cormack, S.J., Newton, R.U., McGuigan, M.R. and Doyle, T.L. (2008a). Reliability of measures obtained during single and repeated countermovement jumps. *International journal of sports physiology and performance*, *3*(2), pp.131-144.

Cormack, S.J., Newton, R.U. and McGuigan, M.R. (2008b). Neuromuscular and endocrine responses of elite players to an Australian rules football match. *International journal of sports physiology and performance*, *3*(3), pp.359-374.

Cornelissen, V.A. and Fagard, R.H. (2005). Effects of endurance training on blood pressure, blood pressure–regulating mechanisms, and cardiovascular risk factors. *Hypertension, 46*(4), pp.667-675.

Cormie, P., McBride, J.M. and McCaulley, G.O. (2009). Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *The Journal of Strength & Conditioning Research*, *23*(1), pp.177-186.

Coutts, A.J., Crowcroft, S. and Kempton, T. (2017). Developing athlete monitoring systems: theoretical basis and practical applications. *Sport, Recovery, and Performance*, pp. 33-46.

Coutts, A.J. and Duffield, R. (2010). Validity and reliability of GPS devices for measuring movement demands of team sports. *Journal of science and Medicine in Sport*, *13*(1), pp.133-135.

Coutts, A.J. and Reaburn, P. (2008). Monitoring changes in rugby league players' perceived stress and recovery during intensified training. *Perceptual and motor skills*, *106*(3), pp.904-916.

Coutts, A.J., Kempton, T., Sullivan, C., Bilsborough, J., Cordy, J. and Rampinini, E. (2015). Metabolic power and energetic costs of professional Australian Football match-play. *Journal of science and medicine in sport, 18*(2), pp.219-224.

Coutts, A.J., Rampinini, E., Marcora, S.M., Castagna, C. and Impellizzeri, F.M. (2009). Heart rate and blood lactate correlates of perceived exertion during small-sided soccer games. *Journal of Science and Medicine in Sport, 12*(1), pp.79-84.

Coutts, A., Reaburn, P., Piva, T.J. and Murphy, A. (2007a). Changes in selected biochemical, muscular strength, power, and endurance measures during deliberate overreaching and tapering in rugby league players. *International journal of sports medicine*, *28*(02), pp.116-124.

Coutts, A.J., Reaburn, P., Piva, T.J. and Rowsell, G.J. (2007b). Monitoring for overreaching in rugby league players. *European journal of applied physiology*, *99*(3), pp.313-324.

Coutts, A.J., Slattery, K.M. and Wallace, L.K. (2007c). Practical tests for monitoring performance, fatigue and recovery in triathletes. *Journal of Science and Medicine in Sport, 10*(6), pp.372-381.

Croisier, J.L., Ganteaume, S., Binet, J., Genty, M. and Ferret, J.M. (2008). Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. *The American journal of sports medicine*, *36*(8), pp.1469-1475.
Cross, M.J., Williams, S., Trewartha, G., Kemp, S.P. and Stokes, K.A. (2016). The influence of in-season training loads on injury risk in professional rugby union. *International journal of sports physiology and performance*, *11*(3), pp.350-355.

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 medicine, 43*(10), pp.1025-1042.

Dauty, M. and Collon, S. (2011). Incidence of injuries in French professional soccer players. *International journal of sports medicine*, *32*(12), pp.965-969.

Davis, J.M. (1995). Central and peripheral factors in fatigue. *Journal of sports sciences*, *13*(S1), pp. 49-53.

Dawson, B. (1996). Periodisation of speed and endurance training. *Training for speed and endurance*, pp. 76-96.

de Hoyo, M., Cohen, D.D., Sañudo, B., Carrasco, L., Álvarez-Mesa, A., del Ojo, J.J., Domínguez-Cobo, S., Mañas, V. and Otero-Esquina, C. (2016). Influence of football match time–motion parameters on recovery time course of muscle damage and jump ability. *Journal of sports sciences*, *34*(14), pp.1363-1370.

Dellal, A., Chamari, K., Wong, D.P., Ahmaidi, S., Keller, D., Barros, R., Bisciotti, G.N. and Carling, C. (2011). Comparison of physical and technical performance in European soccer match-play: FA Premier League and La Liga. *European Journal of Sport Science*, *11*(1), pp.51-59.

Dellal, A., Lago-Peñas, C., Rey, E., Chamari, K. and Orhant, E. (2015). The effects of a congested fixture period on physical performance, technical activity and injury rate during matches in a professional soccer team. *Br J Sports Med*, *49*(6), pp.390-394.

Dennis, R., Farhart, R., Goumas, C. and Orchard, J. (2003). Bowling workload and the risk of injury in elite cricket fast bowlers. *Journal of Science and Medicine in Sport*, *6*(3), pp.359-367.

Di Prampero, P.E., Fusi, S., Sepulcri, L., Morin, J.B., Belli, A. and Antonutto, G. (2005). Sprint running: a new energetic approach. *Journal of experimental Biology, 208*(14), pp.2809-2816.

Di Salvo, V., Baron, R., Tschan, H., Montero, F.C., Bachl, N. and Pigozzi, F. (2007). Performance characteristics according to playing position in elite soccer. *International journal of sports medicine*, *28*(03), pp.222-227.

Di Salvo, V., Pigozzi, F., González-Haro, C., Laughlin, M.S. and De Witt, J.K. (2013). Match performance comparison in top English soccer leagues. *International journal of sports medicine*, *34*(06), pp.526-532.

Djaoui, L., Wong, D.P., Pialoux, V., Hautier, C., Da Silva, C.D., Chamari, K. and Dellal, A. (2014). Physical activity during a prolonged congested period in a top-class European football team. *Asian journal of sports medicine*, *5*(1), p.47-53.

Docherty, D., Wenger, H.A. and Neary, P. (1988). Time-motion analysis related to the physiological demands of rugby. *Journal of Human Movement Studies, 14*(6), pp.269-277.

Drust, B., Atkinson, G. and Reilly, T. (2007). Future perspectives in the evaluation of the physiological demands of soccer. *Sports Medicine, 37*(9), pp.783-805.

Drust, B., Reilly, T. and Cable, N.T. (2000). Physiological responses to laboratory-based soccer-specific intermittent and continuous exercise. *Journal of sports sciences, 18*(11), pp.885-892.

Dupont, G., Nedelec, M., McCall, A., McCormack, D., Berthoin, S. and Wisløff, U. (2010). Effect of 2 soccer matches in a week on physical performance and injury rate. *The American journal of sports medicine*, *38*(9), pp.1752-1758.

Edgecomb, S.J. and Norton, K.I. (2006). Comparison of global positioning and computer-based tracking systems for measuring player movement distance during Australian football. *Journal of science and Medicine in Sport, 9*(1-2), pp.25-32

Edwards S. (1993). *The Heart Rate Monitor Book*. Sacramento, CA: Fleet Feet Press

Eirale, C., Tol, J.L., Farooq, A., Smiley, F. and Chalabi, H. (2013). Low injury rate strongly correlates with team success in Qatari professional football. *Br J Sports Med*, *47*(12), pp.807-808.

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

Ekstrand, J. (2013). Keeping your top players on the pitch: the key to football medicine at a professional level. *British Journal of Sports Medicine, 47,* pp.723-724.

Ekstrand, J. and Gillquist, J. (1982). The frequency of muscle tightness and injuries in soccer players. *The American Journal of Sports Medicine*, *10*(2), pp.75-78.

Ekstrand, J. and Gillquist, J. (1983). Soccer injuries and their mechanisms: a prospective study. *Medicine and science in sports and exercise*, *15*(3), pp.267-270.

Ekstrand, J., Hägglund, M. and Waldén, M. (2011). Epidemiology of muscle injuries in professional football (soccer). *The American journal of sports medicine*, *39*(6), pp.1226-1232.

Ekstrand, J., Hägglund, M. and Waldén, M. (2011). Injury incidence and injury patterns in professional football: the UEFA injury study. *British journal of sports medicine*, *45*(7), pp.553-558.

Ekstrand, J., Hägglund, M., Kristenson, K., Magnusson, H. and Waldén, M. (2013). Fewer ligament injuries but no preventive effect on muscle injuries and severe injuries: an 11-year follow-up of the UEFA Champions League injury study. *Br J Sports Med*, *47*(12), pp.732-737.

Ekstrand, J., Waldén, M. and Hägglund, M. (2004a). A congested football calendar and the wellbeing of players: correlation between match exposure of European footballers before the World Cup 2002 and their injuries and performances during that World Cup. *British journal of sports medicine*, *38*(4), pp.493-497.

Ekstrand, J., Waldén, M. and Hägglund, M. (2004b). Risk for injury when playing in a national football team. *Scandinavian journal of medicine & science in sports*, *14*(1), pp.34-38.

Ekstrand, J., Waldén, M. and Hägglund, M. (2016). Hamstring injuries have increased by 4% annually in men's professional football, since 2001: a 13-year longitudinal analysis of the UEFA Elite Club injury study. *Br J Sports Med*, *50*(12), pp.731-737.

Engebretsen, A.H., Myklebust, G., Holme, I., Engebretsen, L. and Bahr, R. (2010). Intrinsic risk factors for hamstring injuries among male soccer players: a prospective cohort study. *The American journal of sports medicine*, *38*(6), pp.1147-1153.

Enoka, R.M. and Stuart, D.G. (1992). Neurobiology of muscle fatigue. *Journal of applied physiology*, *72*(5), pp.1631-1648.

Esposito, F., Impellizzeri, F.M., Margonato, V., Vanni, R., Pizzini, G. and Veicsteinas, A. (2004). Validity of heart rate as an indicator of aerobic demand during soccer activities in amateur soccer players. *European journal of applied physiology*, *93*(1-2), pp.167-172.

Fanchini, M., Rampinini, E., Riggio, M., Coutts, A.J., Pecci, C. and McCall, A. (2018). Despite association, the acute: chronic work load ratio does not predict non-contact injury in elite footballers. *Science and Medicine in Football*, *2*(2), pp.108-114.

Farrow, D., Pyne, D. and Gabbett, T. (2008). Skill and physiological demands of open and closed training drills in Australian football. *International Journal of Sports Science & Coaching*, *3*(4), pp.489-499.

Fawcett, T. (2006). An introduction to ROC analysis. *Pattern recognition letters*, *27*(8), pp.861-874.

Fernandes, O. and Caixinha, P. (2003). A new method of time-motion analysis for soccer training and competition. *In V World Congress of Science and Football,* pp. 11-15.

Folgado, H., Duarte, R., Marques, P. and Sampaio, J. (2015). The effects of congested fixtures period on tactical and physical performance in elite football. *Journal of sports sciences*, *33*(12), pp.1238-1247.

Foster, C. (1998). Monitoring training in athletes with reference to overtraining syndrome. *Medicine and science in sports and exercise*, *30*, pp.1164-1168.

Foster, C., Florhaug, J.A., Franklin, J., Gottschall, L., Hrovatin, L.A., Parker, S., Doleshal, P. and Dodge, C. (2001). A new approach to monitoring exercise training. *The Journal of Strength & Conditioning Research*, *15*(1), pp.109-115.

Foster, C., Hector, L.L., Welsh, R., Schrager, M., Green, M.A. and Snyder, A.C. (1995). Effects of specific versus cross-training on running performance. *European journal of applied physiology and occupational physiology*, *70*(4), pp.367-372.

Foster, C. (1998). Monitoring training in athletes with reference to overtraining syndrome. *Medicine and science in sports and exercise, 30*, pp.1164-1168.

Fousekis, K., Tsepis, E. and Vagenas, G. (2010). Lower limb strength in professional soccer players: profile, asymmetry, and training age. *Journal of sports science & medicine*, *9*(3), p.364-373.

Fousekis, K., Tsepis, E., Poulmedis, P., Athanasopoulos, S. and Vagenas, G. (2011). Intrinsic risk factors of non-contact quadriceps and hamstring strains in soccer: a prospective study of 100 professional players. *British journal of sports medicine*, *45*(9), pp.709-714.

Freitas, V.H., Nakamura, F.Y., Miloski, B., Samulski, D. and Bara-Filho, M.G. (2014). Sensitivity of physiological and psychological markers to training load intensification in volleyball players. *Journal of sports science & medicine*, *13*(3), p.571-579.

Fry, A.C., Schilling, B.K., Weiss, L.W. and Chiu, L.Z. (2006). β2-Adrenergic receptor downregulation and performance decrements during high-intensity resistance exercise overtraining. *Journal of Applied Physiology*, *101*(6), pp.1664-1672.

Furlan, R., Piazza, S., Dell'Orto, S., Gentile, E., Cerutti, S., Pagani, M. and Malliani, A. (1993). Early and late effects of exercise and athletic training on neural mechanisms controlling heart rate. *Cardiovascular research, 27*(3), pp.482-488.

Gabbe, B.J., Bennell, K.L., Finch, C.F., Wajswelner, H. and Orchard, J.W. (2006a). Predictors of hamstring injury at the elite level of Australian football. *Scandinavian journal of medicine & science in sports*, *16*(1), pp.7-13.

Gabbe, B.J., Branson, R. and Bennell, K.L. (2006b). A pilot randomised controlled trial of eccentric exercise to prevent hamstring injuries in community-level Australian Football. *Journal of science and medicine in sport*, *9*(1-2), pp.103-109.

Gabbett, T.J. (2004a). Influence of training and match intensity on injuries in rugby league. *Journal of sports sciences*, *22*(5), pp.409-417.

Gabbett, T.J. (2004b). Reductions in pre-season training loads reduce training injury rates in rugby league players. *Br J Sports Med. 38*(6), pp.743–749.

Gabbett, T.J. (2016). The training—injury prevention paradox: should athletes be training smarter and harder?. *Br J Sports Med*, *50*(5), pp.273-280.

Gabbett, T.J. and Domrow, N. (2005). Risk factors for injury in subelite rugby league players. *The American Journal of Sports Medicine*, *33*(3), pp.428-434.

Gabbett, T.J. and Domrow, N. (2007). Relationships between training load, injury, and fitness in sub-elite collision sport athletes. *Journal of sports sciences*, *25*(13), pp.1507-1519.

Gabbett, T.J. and Ullah, S. (2012). Relationship between running loads and soft-tissue injury in elite team sport athletes. *The Journal of Strength & Conditioning Research*, *26*(4), pp.953-960.

Gabbett, T.J. (2010). GPS analysis of elite women's field hockey training and competition. *The Journal of Strength & Conditioning Research, 24*(5), pp.1321-1324.

Gabbett, T.J. (2016). The training—injury prevention paradox: should athletes be training smarter and harder? *Br J Sports Med*, *50*(5), pp.273-280.

Gamelin, F.X., Berthoin, S., Sayah, H., Libersa, C. and Bosquet, L. (2007). Effect of training and detraining on heart rate variability in healthy young men. *International journal of sports medicine, 28*(07), pp.564-570.

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

Garrett, J.W. (1990). Muscle strain injuries: clinical and basic aspects. *Medicine and science in sports and exercise*, *22*(4), pp.436-443.

Garrett Jr, W.E. (1996). Muscle strain injuries. *The American journal of sports medicine*, *24*(6), pp.2-8.

Garrett, W.E. and Kirkendall, D.T. (2000). *Exercise and sport science*. Lippincott Williams & Wilkins.

Garrett JR, W.E., Safran, M.R., Seaber, A.V., Glisson, R.R. and Ribbeck, B.M. (1987). Biomechanical comparison of stimulated and nonstimulated skeletal muscle pulled to failure. *The American journal of sports medicine*, *15*(5), pp.448-454.

Gathercole, R.J., Stellingwerff, T. and Sporer, B.C. (2015a.) Effect of acute fatigue and training adaptation on countermovement jump performance in elite snowboard cross athletes. *The Journal of Strength & Conditioning Research*, *29*(1), pp.37-46.

Gathercole, R., Sporer, B., Stellingwerff, T. and Sleivert, G. (2015b). Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. *International journal of sports physiology and performance*, *10*(1), pp.84-92.

Gaudino, P., Iaia, F.M., Alberti, G., Strudwick, A.J., Atkinson, G. and Gregson, W. (2013). Monitoring training in elite soccer players: systematic bias between running speed and metabolic power data. *International journal of sports medicine*, *34*(11), pp.963-968.

Gordon, A.M., Huxley, A.F. and Julian, F.J. (1966). The variation in isometric tension with sarcomere length in vertebrate muscle fibres. *The Journal of physiology*, *184*(1), pp.170-192.

Goto, K., Ishii, N., Mizuno, A. and Takamatsu, K. (2007). Enhancement of fat metabolism by repeated bouts of moderate endurance exercise. *Journal of Applied Physiology*, *102*(6), pp.2158-2164.

Grace, T.G., Sweetser, E.R., Nelson, M.A., Ydens, L.R. and Skipper, B.J. (1984). Isokinetic muscle imbalance and knee-joint injuries. A prospective blind study. *The Journal of bone and joint surgery. American volume*, *66*(5), pp.734-740.

Graham-Smith, P., Jones, P.A., Comfort, P. and Munro, A.G. (2013). Assessment of knee flexor and extensor muscle balance. *International Journal of Athletic Therapy and Training*, *18*(5), pp.1-5.

Gray, A.J., Jenkins, D., Andrews, M.H., Taaffe, D.R. and Glover, M.L. (2010). Validity and reliability of GPS for measuring distance travelled in field-based team sports. *Journal of Sports Sciences, 28*(12), pp.1319-1325.

Green, J.M., McLester, J.R., Crews, T.R., Wickwire, P.J., Pritchett, R.C. and Lomax, R.G. (2006). RPE association with lactate and heart rate during high-intensity interval cycling. *Medicine and science in sports and exercise*, *38*(1), pp.167-172.

Greig, M. and Siegler, J.C. (2009). Soccer-specific fatigue and eccentric hamstrings muscle strength. *Journal of athletic training*, *44*(2), pp.180-184.

Groslambert, A. and Mahon, A.D. (2006). Perceived exertion. *Sports medicine, 36*(11), pp.911-928.

Hägglund, M., Waldén, M., Magnusson, H., Kristenson, K., Bengtsson, H. and Ekstrand, J. (2013). Injuries affect team performance negatively in professional football: an 11-year follow-up of the UEFA Champions League injury study. *Br J Sports Med*, *47*(12), pp.738-742.

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

Harries, S.K., Lubans, D.R. and Callister, R. (2015). Systematic review and meta-analysis of linear and undulating periodized resistance training programs on muscular strength. *The Journal of Strength & Conditioning Research*, *29*(4), pp.1113-1125.

Hartmann, H., Bob, A., Wirth, K. and Schmidtbleicher, D. (2009). Effects of different periodization models on rate of force development and power ability of the upper extremity. *The Journal of Strength & Conditioning Research*, *23*(7), pp.1921-1932.

Hartwig, T.B., Naughton, G. and Searl, J. (2008). Defining the volume and intensity of sport participation in adolescent rugby union players. *International journal of sports physiology and performance*, *3*(1), pp.94-106.

Hartwig, T.B., Naughton, G. and Searl, J. (2011). Motion analyses of adolescent rugby union players: a comparison of training and game demands. *The Journal of Strength & Conditioning Research, 25*(4), pp.966-972.

Harvill, L.M. (1991). Standard error of measurement. *Educational Measurement: issues and practice*, *10*(2), pp.33-41.

Hautala, A.J., Kiviniemi, A.M. and Tulppo, M.P. (2009). Individual responses to aerobic exercise: the role of the autonomic nervous system. *Neuroscience & Biobehavioral Reviews, 33*(2), pp.107-115.

Hautala, A.J., Mäkikallio, T.H., Seppänen, T., Huikuri, H.V. and Tulppo, M.P. (2003). Short-term correlation properties of R–R interval dynamics at different exercise intensity levels. *Clinical physiology and functional imaging, 23*(4), pp.215-223.

Hautala, A., Tulppo, M.P., Mäkikallio, T.H., Laukkanen, R., Nissilä, S. and Huikuri, H.V. (2001). Changes in cardiac autonomic regulation after prolonged maximal exercise. *Clinical Physiology, 21*(2), pp.238-245.

Hawkins, R.D., Hulse, M.A., Wilkinson, C., Hodson, A. and Gibson, M. (2001). The association football medical research programme: an audit of injuries in professional football. *British journal of sports medicine*, *35*(1), pp.43-47.

Hebestreit, H. and Bar-Or, O. (1998). Influence of climate on heart rate in children: comparison between intermittent and continuous exercise. *European journal of applied physiology and occupational physiology, 78*(1), pp.7-12.

Heiderscheit, B.C., Hoerth, D.M., Chumanov, E.S., Swanson, S.C., Thelen, B.J. and Thelen, D.G. (2005). Identifying the time of occurrence of a hamstring strain injury during treadmill running: a case study. *Clinical Biomechanics*, *20*(10), pp.1072-1078.

Heiser, T.M., Weber, J., Sullivan, G., Clare, P. and Jacobs, R.R. (1984). Prophylaxis and management of hamstring muscle injuries in intercollegiate football players. *The American Journal of Sports Medicine*, *12*(5), pp.368-370.

Heishman, A.D., Curtis, M.A., Saliba, E., Hornett, R.J., Malin, S.K. and Weltman, A.L. (2018). Noninvasive assessment of internal and external player load: implications for optimizing athletic performance. *The Journal of Strength & Conditioning Research*, *32*(5), pp.1280-1287.

Heishman, A.D., Daub, B.D., Miller, R.M., Freitas, E.D., Frantz, B.A. and Bemben, M.G. (2020). Countermovement jump reliability performed with and without an arm swing in NCAA division 1 intercollegiate basketball players. *The Journal of Strength & Conditioning Research*, *34*(2), pp.546-558.

Helgerud, J., Engen, L.C., Wisløff, U. and Hoff, J. (2001). Aerobic endurance training improves soccer performance. *Medicine & Science in Sports & Exercise*, *33*(11), pp.1925-1931.

Henderson, G., Barnes, C.A. and Portas, M.D. (2010). Factors associated with increased propensity for hamstring injury in English Premier League soccer players. *Journal of Science and Medicine in Sport*, *13*(4), pp.397-402.

Herman, L., Foster, C., Maher, M.A., Mikat, R.P. and Porcari, J.P. (2006). Validity and reliability of the session RPE method for monitoring exercise training intensity. *South African Journal of Sports Medicine, 18*(1), pp.14-17.

Hill-Haas, S., Coutts, A., Rowsell, G. and Dawson, B. (2008). Variability of acute physiological responses and performance profiles of youth soccer players in small-sided games. *Journal of science and medicine in sport*, *11*(5), pp.487-490.

Hill-Haas, S.V., Dawson, B., Impellizzeri, F.M. and Coutts, A.J. (2011). Physiology of small-sided games training in football. *Sports medicine, 41*(3), pp.199-220.

Hoff, J., Wisløff, U., Engen, L.C., Kemi, O.J. and Helgerud, J. (2002). Soccer specific aerobic endurance training. *British journal of sports medicine, 36*(3), pp.218-221.

Houmard, J.A. (1991). Impact of reduced training on performance in endurance athletes. *Sports Medicine*, *12*(6), pp.380-393.

Houmard, J.A. and Johns, R.A. (1994). Effects of taper on swim performance. *Sports Medicine*, *17*(4), pp.224-232.

HPU Quick Start Booklet, 2015. Retrieved from http://gpsports.com/wp-content/uploads/2015/10/HPU-Quick-Start-Booklet-2015-v-4.pdf. Last accessed 20/01/2020.

Hulin, B.T. (2017). The never-ending search for the perfect acute: chronic workload ratio: what role injury definition? *Br J Sports Med. 51*(13), pp.991–992.

Hulin, B.T., Gabbett, T.J., Blanch, P., Chapman, P., Bailey, D. and Orchard, J.W. (2014). Spikes in acute workload are associated with increased injury risk in elite cricket fast bowlers. *Br J Sports Med*, *48*(8), pp.708-712.

Hulin, B.T., Gabbett, T.J., Caputi, P., Lawson, D.W., Sampson, J.A. (2016a). Low chronic workload and the acute: chronic workload ratio are more predictive of injury than between-match recovery time: a two-season prospective cohort study in elite rugby league players. *Br J Sports Med. 50*(16), pp.1008–1012.

Hulin, B.T., Gabbett, T.J., Lawson, D.W., Caputi, P. and Sampson, J.A. (2016b). The acute: chronic workload ratio predicts injury: high chronic workload may decrease injury risk in elite rugby league players. *Br J Sports Med*, *50*(4), pp.231-236.

Huxley, D.J., O'Connor, D. and Healey, P.A. (2014). An examination of the training profiles and injuries in elite youth track and field athletes. *European journal of sport science*, *14*(2), pp.185-192.

Iellamo, F., Pigozzi, F., Spataro, A., Di Salvo, A., Fagnani, F., Roselli, A., Rizzo, M., Malacarne, M., Pagani, M. and Lucini, D. (2006). Autonomic and psychological adaptations in Olympic rowers. *Journal of sports medicine and physical fitness, 46*(4), p.598-604.

Impellizzeri, F.M., Marcora, S.M. and Coutts, A.J. (2019). Internal and external training load: 15 years on. *International journal of sports physiology and performance*, *14*(2), pp.270-273.

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

Impellizzeri, F.M., Rampinini, E. and Marcora, S.M. (2005). Physiological assessment of aerobic training in soccer. *Journal of sports sciences*, *23*(6), pp.583-592.

Impellizzeri, F.M., Rampinini, E., Coutts, A.J., Sassi, A. and Marcora, S.M. (2004). Use of RPE-based training load in soccer. *Medicine & Science in sports & exercise, 36*(6), pp.1042-1047.

Ingebrigtsen, J., Bendiksen, M., Randers, M.B., Castagna, C., Krustrup, P. and Holtermann, A. (2012). Yo-Yo IR2 testing of elite and sub-elite soccer players: performance, heart rate response and correlations to other interval tests. *Journal of sports sciences*, *30*(13), pp.1337-1345.

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

Isaacs, L.D. (1998). Comparison of the vertec and just jump systems for measuring height of vertical jump by young children. *Perceptual and motor skills*, *86*(2), pp.659-663.

Issurin, V. (2008). Block periodization versus traditional training theory: a review. *Journal of sports medicine and physical fitness*, *48*(1), p.65-75.

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

Issurin, V. (2008). *Principles and basics of advanced training of athletes.* Muskegon (MI): Ultimate Athletes Concepts Publisher.

Issurin, V. and Kaverin, V. (1985). Planning and design of annual preparation cycle in canoe-kayak paddling. *Grebnoj sport (rowing, canoeing, kayaking). Moscow: FiS Publisher*, pp.25-9.

Issurin, V.B. (2010). New horizons for the methodology and physiology of training periodization. *Sports medicine*, *40*(3), pp.189-206.

Ivy, J.L., Lee, M.C., Brozinick Jr, J.T. and Reed, M.J. (1988). Muscle glycogen storage after different amounts of carbohydrate ingestion. *Journal of applied Physiology*, *65*(5), pp.2018-2023.

James, N. (2006). The role of notational analysis in soccer coaching. *International Journal of Sports Science & Coaching, 1*(2), pp.185-198.

Jennings, D., Cormack, S., Coutts, A.J., Boyd, L. and Aughey, R.J. (2010). The validity and reliability of GPS units for measuring distance in team sport specific running patterns. *International journal of sports physiology and performance, 5*(3), pp.328-341

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. *Journal of sports sciences*, *29*(11), pp.1161-1166.

Johns, R.A., Houmard, J.A., Kobe, R.W., Hortobágyi, T., Bruno, N.J., Wells, J.M. and Shinebarger, M.H. (1992). Effects of taper on swim power, stroke distance, and performance. *Medicine and science in sports and exercise*, *24*(10), pp.1141-1146.

Johnson, J.N. (2003). Competitive swimming illness and injury: common conditions limiting participation. *Current sports medicine reports*, *2*(5), pp.267-271.

Johnston, R.J., Watsford, M.L., Pine, M.J., Spurrs, R.W. and Sporri, D. (2013). Assessment of 5 Hz and 10 Hz GPS units for measuring athlete movement demands. *International Journal of performance analysis in sport*, *13*(1), pp.262-274.

Katz, A.T. and Sahlin, K. (1988). Regulation of lactic acid production during exercise. *Journal of applied physiology*, *65*(2), pp.509-518.

Kempton, T., Sullivan, C., Bilsborough, J.C., Cordy, J. and Coutts, A.J. (2015). Match-to-match variation in physical activity and technical skill measures in professional Australian Football. *Journal of Science and Medicine in Sport*, *18*(1), pp.109-113.

Kendall, G., 2008. Scheduling English football fixtures over holiday periods. *Journal of the Operational Research Society*, *59*(6), pp.743-755.

King, D.A., Hume, P.A., Milburn, P.D. and Guttenbeil, D. (2010). Match and training injuries in rugby league. *Sports Medicine, 40*(2), pp.163-178.

Kirkendall, D.T. (2007). Issues in training the female player. *British journal of sports medicine, 41*(suppl 1), pp.64-67.

Komi, P.V. (2000). Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *Journal of biomechanics*, *33*(10), pp.1197-1206.

Koulouris, G., Connell, D.A., Brukner, P. and Schneider-Kolsky, M. (2007). Magnetic resonance imaging parameters for assessing risk of recurrent hamstring injuries in elite athletes. *The American journal of sports medicine*, *35*(9), pp.1500-1506.

Kraemer, W.J. and Fleck, S.J. (2007). *Optimizing strength training: designing nonlinear periodization workouts*. Human Kinetics.

Kraemer, W.J., French, D.N., Paxton, N.J., Hakkinen, K., Volek, J.S., Sebastianelli, W.J., Putukian, M., Newton, R.U., Rubin, M.R., Gómez, A.L. and Vescovi, J.D. (2004). Changes in exercise performance and hormonal concentrations over a big ten soccer season in starters and nonstarters. *Journal of Strength and Conditioning Research*, *18*(1), pp.121-128.

Krustrup, P., Mohr, M., Ellingsgaard, H. and Bangsbo, J. (2005). Physical demands during an elite female soccer game: importance of training status. *Medicine and science in sports and exercise*, *37*(7), p.1242-1248.

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. *Medicine and science in sports and exercise*, *38*(6), pp.1165-1174.

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. *Medicine & Science in Sports & Exercise*, *35*(4), pp.697-705.

Krustrup, P., Zebis, M., Jensen, J.M. and Mohr, M. (2010). Game-induced fatigue patterns in elite female soccer. *The Journal of Strength & Conditioning Research*, *24*(2), pp.437-441.

Kujala, U.M., Orava, S. and Järvinen, M. (1997). Hamstring injuries. *Sports medicine*, *23*(6), pp.397-404.

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), pp.2111-2117.

Lamberts, R.P., Rietjens, G.J., Tijdink, H.H., Noakes, T.D. and Lambert, M.I. (2010). Measuring submaximal performance parameters to monitor fatigue and predict cycling performance: a case study of a world-class cyclo-cross cyclist. *European journal of applied physiology, 108*(1), pp.183-190.

Larsson, P. (2003). Global positioning system and sport-specific testing. *Sports medicine, 33*(15), pp.1093-1101.

Laws of the Game and FA Rules. Retrieved from http://www.thefa.com/football-rules-governance/lawsandrules/laws/football-11-11/law-4---the-players-equipment. Last accessed 05/01/2019.

Lee, M.J., Reid, S.L., Elliott, B.C. and Lloyd, D.G. (2009). Running biomechanics and lower limb strength associated with prior hamstring injury. *Med Sci Sports Exerc*, *41*(10), pp.1942-1951.

Legg, D. and Burnham, R. (1999). In-season shoulder abduction strength changes in football players. *The Journal of Strength & Conditioning Research*, *13*(4), pp.381-383.

Lewin, G. (1989). The incidence of injury in an English professional soccer club during one competitive season. *Physiotherapy*, *75*(10), pp.601-605.

Liebermann, D.G., Katz, L., Hughes, M.D., Bartlett, R.M., McClements, J. and Franks, I.M. (2002). Advances in the application of information technology to sport performance. *Journal of sports sciences, 20*(10), pp.755-769.

Li, R., Deurenberg, P. and Hautvast, J.G.J. (1993). A critical evaluation of heart rate monitoring to assess energy expenditure in individuals. *The American journal of clinical nutrition, 58*(5), pp.602-607.

Lidor, R., Blumenstein, B. and Tenenbaum, G. (2007). Periodization and planning of psychological preparation in individual and team sports. *Psychology of sport training*, pp.137-161.

Lieber, R.L. and Friden, J. (1988). Selective damage of fast glycolytic muscle fibres with eccentric contraction of the rabbit tibialis anterior. *Acta Physiologica Scandinavica*, *133*(4), pp.587-588.

Los Arcos, A., Martínez-Santos, R., Yanci, J., Mendiguchia, J. and Méndez-Villanueva, A. (2015). Negative associations between perceived training load, volume and changes in physical fitness in professional soccer players. *Journal of sports science & medicine*, *14*(2), p.394.

Los Arcos, A., Yanci, J., Mendiguchia, J. and Gorostiaga, E.M. (2014). Rating of muscular and respiratory perceived exertion in professional soccer players. *The Journal of Strength & Conditioning Research*, *28*(11), pp.3280-3288.

Lovell, R. and Abt, G. (2013). Individualization of time–motion analysis: a case-cohort example. *International journal of sports physiology and performance*, *8*(4), pp.456-458.

Lu, D., Howle, K., Waterson, A., Duncan, C. and Duffield, R. (2017). Workload profiles prior to injury in professional soccer players. *Science and Medicine in Football*, *1*(3), pp.237-243.

Lucia, A., Hoyos, J., Carvajal, A. and Chicharro, J.L. (1999). Heart rate response to professional road cycling: The Tour de France. *International Journal of Sports Medicine*, *20*(03), pp.167-172.

Lucia, A., Hoyos, J., Santalla, A., Earnest, C. and Chicahrro, J.L. (2003). Tour de France versus Vuelta a Espana: which is harder? *Medicine & Science in Sports & Exercise*, *35*(5), pp.872-878.

Lyman, S., Fleisig, G.S., Waterbor, J.W., Funkhouser, E.M., Pulley, L., Andrews, J.R., Osinski, E.D. and Roseman, J.M. (2001). Longitudinal study of elbow and shoulder pain in youth baseball pitchers. *Medicine and science in sports and exercise*, *33*(11), pp.1803-1810.

MacIntosh, B.R., Gardiner, P.F. and McComas, A.J. (2006). *Skeletal muscle: form and function*. Human Kinetics.

Mair, S.D., Seaber, A.V., Glisson, R.R. and Garrett JR, W.E. (1996). The role of fatigue in susceptibility to acute muscle strain injury. *The American Journal of Sports Medicine*, *24*(2), pp.137-143.

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. *European heart journal*, *17*(3), pp.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. *International journal of sports physiology and performance*, *10*(4), pp.489-497.

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), pp.752-757.

Malone, S., Roe, M., Doran, D.A., Gabbett, T.J. and Collins, K.D. (2016). Aerobic Fitness and Playing Experience Protect Against Spikes in Workload: The Role of the Acute: Chronic Workload Ratio on Injury Risk in Elite Gaelic Football. *International journal of sports physiology and performance*, *24*, pp.1-25.

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

Mann, R.V. (1981). A kinetic analysis of sprinting. *Medicine and science in sports and exercise*, *13*(5), pp.325-328.

Manzi, V., D'ottavio, S., Impellizzeri, F.M., Chaouachi, A., Chamari, K. and Castagna, C. (2010). Profile of weekly training load in elite male professional basketball players. *The Journal of Strength & Conditioning Research*, *24*(5), pp.1399-1406.

Markovic, G., Dizdar, D., Jukic, I. and Cardinale, M. (2004). Reliability and factorial validity of squat and countermovement jump tests. *The Journal of Strength & Conditioning Research*, *18*(3), pp.551-555.

Matveyev, L. (1981). *Fundamentals of sports training.* Moscow: Progress Publishers

Mayhew, S.R. and Wenger, H.A. (1985). Time-motion analysis of professional soccer. *Journal of Human Movement Studies*, *11*(1), pp.49-52.

McConell, G.K., Costill, D.L., Widrick, J.J., Hickey, M.S., Tanaka, H. and Gastin, P.B. (1993). Reduced training volume and intensity maintain aerobic capacity but not performance in distance runners. *International journal of sports medicine*, *14*(01), pp.33-37.

McGregor, S.J., Nicholas, C.W., Lakomy, H.K.A. and Williams, C. (1999). The influence of intermittent high-intensity shuttle running and fluid ingestion on the performance of a soccer skill. *Journal of Sports Sciences*, *17*(11), pp.895-903.

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. *International journal of sports physiology and performance*, *5*(3), pp.367-383.

McLellan, C.P., Lovell, D.I. and Gass, G.C. (2011). Performance analysis of elite rugby league match play using global positioning systems. *The Journal of Strength & Conditioning Research, 25*(6), pp.1703-1710.

Meilion, M.B. (1991). Common cycling injuries: management and prevention. *Sports Med*, *11*(1), pp.52-70.

Merri, M., Farden, D.C., Mottley, J.G. and Titlebaum, E.L. (1990). Sampling frequency of the electrocardiogram for spectral analysis of the heart rate variability. *IEEE Transactions on Biomedical Engineering, 37*(1), pp.99-106.

Minett, G.M. and Duffield, R. (2014). Is recovery driven by central or peripheral factors? A role for the brain in recovery following intermittent-sprint exercise. *Frontiers in physiology*, *5*, p.24. (https://doi.org/10.3389/fphys.2014.00024)

Miyagi, O., Ohashi, J. and Kitagawa, K. (1999). Motion characteristics of an elite soccer player during a game. *Journal of Sports Sciences, 17*(10), pp.816.

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

Mohr, M., Krustrup, P., Andersson, H., Kirkendal, D. and Bangsbo, J. (2008). Match activities of elite women soccer players at different performance levels. *The Journal of Strength & Conditioning Research*, *22*(2), pp.341-349.

Moir, G., Button, C., Glaister, M. and Stone, M.H. (2004). Influence of familiarization on the reliability of vertical jump and acceleration sprinting performance in physically active men. *Journal of strength and conditioning research*, *18*(2), pp.276-280.

Montano, N., Ruscone, T.G., Porta, A., Lombardi, F., Pagani, M. and Malliani, A. (1994). Power spectrum analysis of heart rate variability to assess the changes in sympathovagal balance during graded orthostatic tilt. *Circulation, 90*(4), pp.1826-1831.

Montgomery III, W.H., Pink, M. and Perry, J. (1994). Electromyographic analysis of hip and knee musculature during running. *The American journal of sports medicine*, *22*(2), pp.272-278.

Mooney, M.G., Cormack, S., O'Brien, B.J., Morgan, W.M. and McGuigan, M. (2013). Impact of neuromuscular fatigue on match exercise intensity and performance in elite Australian football. *The Journal of Strength & Conditioning Research*, *27*(1), pp.166-173.

Mooney, M., O’Brien, B., Cormack, S., Coutts, A., Berry, J. and Young, W. (2011). The relationship between physical capacity and match performance in elite Australian football: a mediation approach. *Journal of Science and Medicine in Sport*, *14*(5), pp.447-452.

Moreira, A., Bilsborough, J.C., Sullivan, C.J., Cianciosi, M., Aoki, M.S. and Coutts, A.J. (2015). Training periodization of professional Australian football players during an entire Australian Football League season. *International journal of sports physiology and performance*, *10*(5), pp.566-571.

Morgan, D.L. (1990). New insights into the behavior of muscle during active lengthening. *Biophysical journal*, *57*(2), pp.209-221.

Morgan, W. P. (1994). Psychological components of effort sense. *Medicine & Science in Sports & Exercise, 26*(9), 1071-1077.

Morgans, R., Orme, P., Anderson, L. and Drust, B. (2014a). Principles and practices of training for soccer. *Journal of Sport and Health Science*, *3*(4), pp.251-257.

Morgans, R., Orme, P., Anderson, L., Drust, B. and Morton, J.P. (2014b). An intensive winter fixture schedule induces a transient fall in salivary IgA in english premier league soccer players. *Research in Sports Medicine*, *22*(4), pp.346-354.

Morton, R.H. (1997). Modelling training and overtraining. *Journal of sports sciences*, *15*(3), pp.335-340.

Mujika, I. and Padilla, S. (2003). Scientific bases for precompetition tapering strategies. *Medicine and science in sports and exercise*, *35*(7), pp.1182-1187.

Mujika, I., Padilla, S., Pyne, D. and Busso, T. (2004). Physiological changes associated with the pre-event taper in athletes. *Sports medicine*, *34*(13), pp.891-927.

Nassis, G.P. and Gabbett, T.J. (2016). Is workload associated with injuries and performance in elite football? A call for action. *British journal of sports medicine*, *51*(6), pp.486-487.

Nédélec, M., McCall, A., Carling, C., Legall, F., Berthoin, S. and Dupont, G. (2012). Recovery in soccer. *Sports medicine*, *42*(12), pp.997-1015.

Nédélec, M., McCall, A., Carling, C., Legall, F., Berthoin, S. and Dupont, G. (2013). Recovery in soccer. *Sports medicine*, *43*(1), pp.9-22.

Nicol, C., Avela, J., Komi, P.V. (2006). The stretch-shortening cycle: a model to study naturally occurring neuromuscular fatigue. Sports Medicine, 36(11), pp. 977-999.

Niemela, T.H., Kiviniemi, A.M., Hautala, A.J., Salmi, J.A., Linnamo, V. and Tulppo, M.P. (2008). Recovery pattern of baroreflex sensitivity after exercise. *Medicine and science in sports and exercise, 40*(5), p.864.

Nosse, L.J. (1982). Assessment of selected reports on the strength relationship of the knee musculature. *Journal of Orthopaedic & Sports Physical Therapy*, *4*(2), pp.78-85.

Novacheck, T.F. (1998). The biomechanics of running. *Gait & posture*, *7*(1), pp.77-95.

Ohashi, J., Togari, H. and Isokawa, M., Suzuki., S. (1988). Measuring movement speeds and distances covered during soccer match play. *Science and Football*, pp.329-333.

Ohta, T., Togari, H. and Komiya, Y. (1969). *Game analysis of soccer*. Tokyo: Japanese Football Association.

Olsen, S.J., Fleisig, G.S., Dun, S., Loftice, J. and Andrews, J.R. (2006). Risk factors for shoulder and elbow injuries in adolescent baseball pitchers. *The American journal of sports medicine*, *34*(6), pp.905-912.

Opar, D.A., Williams, M., Timmins, R., Hickey, J., Duhig, S. and Shield, A. (2015). Eccentric hamstring strength and hamstring injury risk in Australian footballers. *Medicine & Science in Sports & Exercise*, *47*(4), pp.857-865.

Orchard, J. (2002). Biomechanics of muscle strain injury. *NZJ Sports Med*, *30*, pp.92-98.

Orchard, J., Marsden, J., Lord, S. and Garlick, D. (1997). Preseason hamstring muscle weakness associated with hamstring muscle injury in Australian footballers. *The American Journal of Sports Medicine*, *25*(1), pp.81-85.

Orchard J.W. (2012). Hamstrings are most susceptible to injury during the early stance phase of sprinting. *British Journal of Sports Medicine*, 46, pp.88-89.

Osgnach, C., Poser, S., Bernardini, R., Rinaldo, R. and Di Prampero, P.E. (2010). Energy cost and metabolic power in elite soccer: a new match analysis approach. *Med Sci Sports Exerc*, *42*(1), pp.170-178.

Osternig, L.R., (1986). Isokinetic dynamometry: implications for muscle testing and rehabilitation. *Exercise and sport sciences reviews*, *14*, pp.45-80.

Pagani, M., Montano, N., Porta, A., Malliani, A., Abboud, F.M., Birkett, C. and Somers, V.K. (1997). Relationship between spectral components of cardiovascular variabilities and direct measures of muscle sympathetic nerve activity in humans. *Circulation, 95*(6), pp.1441-1448.

Pandy, M.G. and Andriacchi, T.P. (2010). Muscle and joint function in human locomotion. *Annual review of biomedical engineering*, *12*, pp.401-433.

Parfitt, G., Eston, R. and Connolly, D., 1996. Psychological affect at different ratings of perceived exertion in high-and low-active women: a study using a production protocol. *Perceptual and motor skills*, *82*(3), pp.1035-1042.

Pearson, D., Faigenbaum, A., Conley, M. and Kraemer, W.J. (2000). The National Strength and Conditioning Association's basic guidelines for the resistance training of athletes. *Strength & Conditioning Journal*, *22*(4), p.14-27.

Pepe, M.S., Janes, H., Longton, G., Leisenring, W. and Newcomb, P. (2004). Limitations of the odds ratio in gauging the performance of a diagnostic, prognostic, or screening marker. *American journal of epidemiology*, *159*(9), pp.882-890.

Pereira, G., Freitas, P.B.D., Barela, J.A., Ugrinowitsch, C., Rodacki, A.L., Kokubun, E. and Fowler, N.E. (2014). Vertical jump fatigue does not affect intersegmental coordination and segmental contribution. *Motriz: Revista de Educação Física*, *20*(3), pp.303-309.

Perrine, J.J. and Edgerton, V.R. (1978). Muscle force-velocity and power-velocity relationships under isokinetic loading. *Medicine and science in sports*, *10*(3), pp.159-166.

Petersen, C., Pyne, D., Portus, M. and Dawson, B. (2009). Validity and reliability of GPS units to monitor cricket-specific movement patterns. *International journal of sports physiology and performance, 4*(3), pp.381-393.

Pikkujamsa, S.M., Makikallio, T.H., Airaksinen, K.J. and Huikuri, H.V. (2001). Determinants and interindividual variation of RR interval dynamics in healthy middle-aged subjects. *American Journal of Physiology-Heart and Circulatory Physiology, 280*(3), pp.1400-1406.

Pinniger, G.J., Steele, J.R. and Groeller, H. (2000). Does fatigue induced by repeated dynamic efforts affect hamstring muscle function? *Medicine and Science in Sports and Exercise*, *32*(3), pp.647-653.

Place, N., Yamada, T., Bruton, J.D. and Westerblad, H. (2010). Muscle fatigue: from observations in humans to underlying mechanisms studied in intact single muscle fibres. *European journal of applied physiology*, *110*(1), pp.1-15.

Pointon, M., Duffield, R., Cannon, J. and Marino, F.E. (2012). Cold water immersion recovery following intermittent-sprint exercise in the heat. *European journal of applied physiology*, *112*(7), pp.2483-2494.

Pyne, D.B. and Martin, D.T. (2011). Fatigue-Insights from individual and team sports. In *Regulation of fatigue in exercise,* pp. 177-186.

Pyne, D.B. and Touretski, G. (1993). An analysis of the training of Olympic sprint champion Alexandre Popov. *Australian Swim Coach*, *10*(5), pp.5-14.

Rampinini, E., Bishop, D., Marcora, S.M., Bravo, D.F., Sassi, R. and Impellizzeri, F.M. (2007). Validity of simple field tests as indicators of match-related physical performance in top-level professional soccer players. *International journal of sports medicine*, *28*(03), pp.228-235.

Rampinini, E., Bosio, A., Ferraresi, I., Petruolo, A., Morelli, A. and Sassi, A. (2011). Match-related fatigue in soccer players. *Medicine & Science in Sports & Exercise*, *43*(11), pp.2161-2170.

Rampinini, E., Impellizzeri, F.M., Castagna, C., Coutts, A.J. and Wisløff, U. (2009). Technical performance during soccer matches of the Italian Serie A league: Effect of fatigue and competitive level. *Journal of science and medicine in sport*, *12*(1), pp.227-233.

Randers, M.B., Rostgaard, T. and Krustrup, P. (2007). Physical match performance and yo-yo IR2 test results of successful and unsuccessful football teams in the Danish premier league. *J Sports Sci Med, 6*(Suppl 10), p.70-71.

Reilly, T. (2006). *The science of training–Soccer: A scientific approach to developing strength, speed and endurance*. Routledge.

Rennie, K.L., Hennings, S.J., Mitchell, J. and Wareham, N.J. (2001). Estimating energy expenditure by heart-rate monitoring without individual calibration. *Medicine and science in sports and exercise, 33*(6), pp.939-945.

Rey, E., Lago-Peñas, C., Lago-Ballesteros, J., Casais, L. and Dellal, A. (2010). The effect of a congested fixture period on the activity of elite soccer players. *Biology of Sport*, *27*(3), pp.181-185.

Rienzi, E., Drust, B., Reilly, T., Carter, E. L. and Martin, A. (2000). Investigation of anthropometric and work-rate profiles of elite South American international soccer players. *Journal of Sports Medicine and Physical Fitness*, 40: 162–169.

Roberts, S., Trewartha, G. and Stokes, K. (2006). A comparison of time–motion analysis methods for field-based sports. *International Journal of Sports Physiology and Performance, 1*(4), pp.388-399.

Robertson, R.J., Goss, F.L., Dube, J., Rutkowski, J., Dupain, M., Brennan, C. and Andreacci, J. (2004). Validation of the adult OMNI scale of perceived exertion for cycle ergometer exercise. *Medicine & Science in Sports & Exercise, 36*(1), pp.102-108.

Robinson, B.F., Epstein, S.E., Beiser, G.D. and Braunwald, E. (1966). Control of heart rate by the autonomic nervous system: studies in man on the interrelation between baroreceptor mechanisms and exercise. *Circulation Research, 19*(2), pp.400-411.

Rogalski, B., Dawson, B., Heasman, J. and Gabbett, T.J. (2013). Training and game loads and injury risk in elite Australian footballers. *Journal of science and medicine in sport*, *16*(6), pp.499-503.

Rollo, I., Impellizzeri, F.M., Zago, M. and Iaia, F.M. (2014). Effects of 1 versus 2 games a week on physical and subjective scores of subelite soccer players. *International Journal of Sports Physiology and Performance*, *9*(3), pp.425-431.

Ronglan, L.T., Raastad, T. and Børgesen, A. (2006). Neuromuscular fatigue and recovery in elite female handball players. *Scandinavian journal of medicine & science in sports*, *16*(4), pp.267-273.

Rothstein, J.M., Lamb, R.L. and Mayhew, T.P. (1987). Clinical uses of isokinetic measurements: critical issues. *Physical Therapy*, *67*(12), pp.1840-1844.

Reilly, T. (1976). A motion analysis of work-rate in different positional roles in professional football match-play. *J Human Movement Studies, 2*, pp.87-97.

Reilly, T. (1997). Energetics of high-intensity exercise (soccer) with particular reference to fatigue. *Journal of sports sciences*, *15*(3), pp.257-263.

Reilly, T. (2006). *The science of training–Soccer: A scientific approach to developing strength, speed and endurance*. Routledge.

Ritchie, D., Hopkins, W.G., Buchheit, M., Cordy, J. and Bartlett, J.D. (2016). Quantification of training and competition load across a season in an elite Australian football club. *International journal of sports physiology and performance*, *11*(4), pp.474-479.

Russell, W.D. (1997). On the current status of rated perceived exertion. *Perceptual and motor skills*, *84*(3), pp.799-808.

Sahlin, K. (1986). Metabolic changes limiting muscle performance. *Biochemistry of Exercise, 6*, pp.323-343.

Salo, M.A., Huikuri, H.V. and Seppanen, T. (2001). Ectopic beats in heart rate variability analysis: effects of editing on time and frequency domain measures. *Annals of noninvasive electrocardiology, 6*(1), pp.5-17.

Schache, A.G., Wrigley, T.V., Baker, R. and Pandy, M.G. (2009). Biomechanical response to hamstring muscle strain injury. *Gait & posture*, *29*(2), pp.332-338.

Schmidt-Olsen, S., Bünemann, L.K., Lade, V. and Brassøe, J.O. (1985). Soccer injuries of youth. *British journal of sports medicine*, *19*(3), pp.161-164.

Scott, B.R., Lockie, R.G., Knight, T.J., Clark, A.C. and Janse de Jonge, X.A. (2013). A comparison of methods to quantify the in-season training load of professional soccer players. *International journal of sports physiology and performance*, *8*(2), pp.195-202.

Sconce, E., Jones, P., Turner, E., Comfort, P. and Graham-Smith, P. (2015). The validity of the Nordic hamstring lower for a field-based assessment of eccentric hamstring strength. *Journal of sport rehabilitation*, *24*(1), pp.13-20.

Scrimgeour, A.G., Noakes, T.D., Adams, B. and Myburgh, K. (1986). The influence of weekly training distance on fractional utilization of maximum aerobic capacity in marathon and ultramarathon runners. *European journal of applied physiology and occupational physiology*, *55*(2), pp.202-209.

Shaffer, F. and Venner, J. (2013). Heart rate variability anatomy and physiology. *Biofeedback, 41*(1), pp.13-25.

Shantarovich, V.V., Narskin, A.G. and Shantarovich, A.V. (2006). Block training system within Olympic preparation cycle of top-level canoekayak paddlers. *Actual problems of high-performance sport towards the XXIX Beijing Olympic Games. Minsk: Research Sport Institute of Belarus*, pp.113-117.

Sheppard, J.M., Cormack, S., Taylor, K.L., McGuigan, M.R. and Newton, R.U. (2008). Assessing the force-velocity characteristics of the leg extensors in well-trained athletes: The incremental load power profile. *The Journal of Strength & Conditioning Research*, *22*(4), pp.1320-1326.

Shiokawa, M., Takahashi, K., Kan, A., Usui, K.O.S., Choi, C.S. and Deguchi, T. (2003). Computer analysis of a soccer game by the DLT method focusing on the movement of the players and the ball. In V World Congress of Science and Football, Lisbon-Portugal. Book of Abstract (Vol. 267).

Silva, J.R., Rebelo, A., Marques, F., Pereira, L., Seabra, A., Ascensão, A. and Magalhães, J. (2013). Biochemical impact of soccer: an analysis of hormonal, muscle damage, and redox markers during the season. *Applied Physiology, Nutrition, and Metabolism*, *39*(4), pp.432-438.

Slattery, K.M., Wallace, L.K., Bentley, D.J. and Coutts, A.J. (2012). Effect of training load on simulated team sport match performance. *Applied Physiology, Nutrition, and Metabolism*, *37*(2), pp.315-322.

Slinde, F., Suber, C., Suber, L., Edwén, C.E. and Svantesson, U. (2008). Test-retest reliability of three different countermovement jumping tests. *The Journal of Strength & Conditioning Research*, *22*(2), pp.640-644.

Soligard, T., Schwellnus, M., Alonso, J.M., Bahr, R., Clarsen, B., Dijkstra, H.P., Gabbett, T., Gleeson, M., Hägglund, M., Hutchinson, M.R. and van Rensburg, C.J. (2016). How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. *Br J Sports Med*, *50*(17), pp.1030-1041.

Spielberger, C.D. (2010). State‐Trait anxiety inventory. *The Corsini encyclopedia of psychology,* pp.1-1.

Sprague, P. and Mann, R.V. (1983). The effects of muscular fatigue on the kinetics of sprint running. *Research quarterly for exercise and sport*, *54*(1), pp.60-66.

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

Stone, M.H., Stone, M. and Sands, W.A. (2007). *Principles and practice of resistance training*. Human Kinetics.

Strudwick, T. (2012). *Science and Soccer*. London: Routledge.

Strudwick, T. and Reilly, T. (2001). Work-rate profiles of elite Premier League football players. *Insight, 2*(2), pp.28-29.

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

Telley, I.A., Stehle, R., Ranatunga, K.W., Pfitzer, G., Stüssi, E. and Denoth, J. (2006). Dynamic behaviour of half-sarcomeres during and after stretch in activated rabbit psoas myofibrils: sarcomere asymmetry but no 'sarcomere popping'. *The Journal of Physiology*, *573*(1), pp.173-185.

Thelen, D.G., Chumanov, E.S., Hoerth, D.M., Best, T.M., Swanson, S.C., Li, L.I., Young, M. and Heiderscheit, B.C. (2005). Hamstring muscle kinematics during treadmill sprinting. *Med Sci Sports Exerc*, *37*(1), pp.108-114.

Theodorou, A. and Cooke, C.B. (1998). Evaluation of the validity and reliability of a 30s vertical jump test. *J Sports Sci*, *16*(1), pp.30-31.

Thomas, J.R., Nelson, J.K. and Silverman, S.J. (2015). *Research methods in physical activity*. Human kinetics.

Thomas, K., Dent, J., Howatson, G. and Goodall, S. (2017). Etiology and recovery of neuromuscular fatigue following simulated soccer match-play. *Medicine & Science in Sports & Exercise*, *49*(5), pp.955-964.

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. *International journal of sports physiology and performance*, *10*(8), pp.958-964.

Thorstensson, A., Grimby, G. and Karlsson, J. (1976). Force-velocity relations and fiber composition in human knee extensor muscles. *Journal of applied physiology*, *40*(1), pp.12-16.

TRACAB Optical Tracking Product Information Sheet. Retrieved from https://chyronhego.com/wp-content/uploads/2019/01/TRACAB-PI-sheet.pdf. Last accessed 04/09/2019.

Tulppo, M.P., Kiviniemi, A.M., Hautala, A.J., Kallio, M., Seppanen, T., Makikallio, T.H. and Huikuri, H.V. (2005). Physiological background of the loss of fractal heart rate dynamics. *Circulation-Hagertown, 112*(3), pp.314-319.

Tulppo, M.P., Makikallio, T.H., Seppänen, T., Laukkanen, R.T. and Huikuri, H.V. (1998). Vagal modulation of heart rate during exercise: effects of age and physical fitness. *American Journal of Physiology-Heart and Circulatory Physiology, 274*(2), pp.424-429.

Tupa, V., Gusenov, F. and Mironenko, I. (1995). Fatigue influenced changes to sprinting technique. *Modern Athlete and Coach*, *33*(3), pp.7-10.

Twist, C. and Highton, J. (2013). Monitoring fatigue and recovery in rugby league players. *International Journal of sports physiology and performance*, *8*(5), pp.467-474.

Vaile, J., Halson, S., Gill, N. and Dawson, B. (2008). Effect of hydrotherapy on the signs and symptoms of delayed onset muscle soreness. *European journal of applied physiology*, *102*(4), pp.447-455.

Valter, D.S., Adam, C., Barry, M. and Marco, C. (2006). Validation of Prozone®: A new video-based performance analysis system. *International Journal of Performance Analysis in Sport, 6*(1), pp.108-119.

Van De Borne, P., Montano, N., Pagani, M., Oren, R. and Somers, V.K. (1997). Absence of low-frequency variability of sympathetic nerve activity in severe heart failure. *Circulation, 95*(6), pp.1449-1454.

Verkhoshansky, Y.U. (1985). *Programming and organization of training*. Moscow: Fizkultura i Sport.

Verhoshanskiy, Y.V. (1988). *Bases of special physical preparation athlete.* Physical culture and sport, Moscow, Russian Federation.

Verrall, G.M., Kalairajah, Y., Slavotinek, J.P. and Spriggins, A.J. (2006). Assessment of player performance following return to sport after hamstring muscle strain injury. *Journal of Science and Medicine in Sport*, *9*(1-2), pp.87-90.

Vellers, H.L., Kleeberger, S.R. and Lightfoot, J.T. (2018). Inter-individual variation in adaptations to endurance and resistance exercise training: genetic approaches towards understanding a complex phenotype. *Mammalian genome*, *29*(1-2), pp.48-62.

Visnes, H., Aandahl, H.Å. and Bahr, R. (2013). Jumper's knee paradox—jumping ability is a risk factor for developing jumper's knee: a 5-year prospective study. *Br J Sports Med*, *47*(8), pp.503-507.

Viru, A.A. and Viru, M. (2001). *Biochemical monitoring of sport training*. Human Kinetics.

Viru, A. and Viru, M. (2000). Nature of training effects. *Exercise and sport science*, pp.67-95.

Waldén, M., Hägglund, M. and Ekstrand, J. (2007). Football injuries during European championships 2004–2005. *Knee Surgery, Sports Traumatology, Arthroscopy*, *15*(9), pp.1155-1162.

Waldron, M., Twist, C., Highton, J., Worsfold, P. and Daniels, M. (2011). Movement and physiological match demands of elite rugby league using portable global positioning systems. *Journal of Sports Sciences, 29*(11), pp.1223-1230.

Wallace, L.K., Slattery, K.M. and Coutts, A.J. (2009). The ecological validity and application of the session-RPE method for quantifying training loads in swimming. *The Journal of Strength & Conditioning Research*, *23*(1), pp.33-38.

Wallin, B.G. and Charkoudian, N. (2007). Sympathetic neural control of integrated cardiovascular function: insights from measurement of human sympathetic nerve activity. *Muscle & nerve, 36*(5), pp.595-614.

Warrel, T.W. (2003). Factors associated with hamstrings injuries: an approach to treatment and preventive measures. *Sports Med*, *17*(5), pp.338-345.

Weltman, A., 1995. *The blood lactate response to exercise* (Vol. 4). Champaign: Human Kinetics.

Wenger, H.A. and Bell, G.J. (1986). The interactions of intensity, frequency and duration of exercise training in altering cardiorespiratory fitness. *Sports medicine*, *3*(5), pp.346-356.

Withers, R.T. (1982). Match analyses of Australian professional soccer players. *J Human Movement Studies*, *8*, pp.159-176.

Witvrouw, E., Mahieu, N., Danneels, L. and McNair, P. (2004). Stretching and injury prevention. *Sports medicine*, *34*(7), pp.443-449.

Woods, C., Hawkins, R., Hulse, M. and Hodson, A. (2002). The Football Association Medical Research Programme: an audit of injuries in professional football—analysis of preseason injuries. *British journal of sports medicine*, *36*(6), pp.436-441.

Worrell, T.W., Perrin, D.H., Gansneder, B.M. and Gieck, J.H. (1991). Comparison of lsokinetic strength and flexibility measures between hamstring injured and noninjured athletes. *Journal of Orthopaedic & Sports Physical Therapy*, *13*(3), pp.118-125.

Yakovlev, N.N., 1955. *Survey on sport biochemistry*. FiS, Moscow.

Yeung, S.S., Suen, A.M. and Yeung, E.W. (2009). A prospective cohort study of hamstring injuries in competitive sprinters: preseason muscle imbalance as a possible risk factor. *British journal of sports medicine*, *43*(8), pp.589-594.

Yu, B., Queen, R.M., Abbey, A.N., Liu, Y., Moorman, C.T. and Garrett, W.E. (2008). Hamstring muscle kinematics and activation during overground sprinting. *Journal of biomechanics*, *41*(15), pp.3121-3126.

Zainuddin, Z., Sacco, P., Newton, M. and Nosaka, K. (2006). Light concentric exercise has a temporarily analgesic effect on delayed-onset muscle soreness, but no effect on recovery from eccentric exercise. *Applied Physiology, Nutrition, and Metabolism*, *31*(2), pp.126-134.

Zeederberg, C., Leach, L., Lambert, E.V., Noakes, T.D., Dennis, S.C. and Hawley, J.A. (1996). The effect of carbohydrate ingestion on the motor skill proficiency of soccer players. *International Journal of Sport Nutrition and Exercise Metabolism*, *6*(4), pp.348-355.

Chapter 8: Appendices

Ethical Approval

Appendix A: Participant Information Sheet

Appendix B: Health Questionnaire

Appendix C: Consent Form

Appendix D: Matches of English League 1 2018/2019 Season and Player Involvement

Appendix A: Participant Information sheet

Effect of Accumulation of Training Load on Neuromuscular Fatigue and hamstring injury in professional football players.

Our research team would like to invite you to participate in our latest study. Before you decide to take part, we would like to ensure that you fully understand the relevance of this research, the possible benefits to you as a participant, the time required to participate, and any risks you may encounter. One of our research team will go through this information sheet and answer any additional questions.

What is the purpose of this research?

The study is investigating the impact of training load of fatigue and injury incidence in professional football players. It is important for medical staff and coaching teams at football clubs to understand how training and match loads on players affects levels of fatigue and risk of injury and illness. This research will assess how measuring training and match performance via GPS can give medical and coaching staff key information about how physically tired the player is as a result of previous training sessions and matches, and how ready they are to perform.

How long am I expected to be involved in the study?

The study will extend over the rest of the 2018-19 football season. You will be required to allow your GPS data collected during training and matches to be used for research purposes.

What will my participation in the study involve?

At the start of the study we will ensure you understand what is involved in the research and ask you to sign a consent form. We will then ask you to fill in a health questionnaire to assure you do not suffer from any medical conditions that will stop you participating in the study as follows:
As usual in every training and match, you will be required to wear a Global Positioning System (GPS) unit and heart rate monitor (training only). The data collected during these sessions will be collected and downloaded in order to measure your activity patterns during the training session or match.

At the start of training sessions immediately before and after matches you will be required to perform a counter movement jump (CMJ) to establish your explosive power performance. The CMJs would be performed a total of 5 times, where 2 jumps would be practice jumps, with the final 3 being for assessment. The highest score jump from the assessment jumps would be recorded. When performing the CMJ, you would be required to place both of your hands on your hips throughout the whole process of the jump. You would then bend your knees to a 90° angle before jumping as high as possible (see Figure 1). From this manoeuvre we will record your jump height, power, and flight time.

Figure 1: Counter-movement Jump Procedure.

You would be required to complete a short wellness questionnaire every morning before arriving for training. The questionnaire includes a rating of your quality of sleep the previous night. After training and matches, you will be asked rate your perceived exertion in the training session or match (i.e. how much effort you feel you had to put in during the session), and your rating of fatigue.

On designated gym session days, we will measure your level of hamstring fatigue via use of a Nordic hamstring curl test. Following a warm up we will ask you to perform a series of Nordic Hamstring Curls. In this test will be required to lower your trunk from a kneeling position (knees flexed at 90°) to the lowest point you find possible and hold the position for 3 seconds (see Figure 2). An assistant will help in holding down the ankles as you lower yourselves. The angle at your knee will be measured and used as an assessment of the hamstring performance. You will be required to perform 3 Nordic hamstring curls. The initial 2 are submaximal performances as a warm up without the isometric hold at the end. The final 1 is with the isometric hold where the angle is measured.

Figure 2: Nordic Hamstring Curl.

What are the benefits of taking part?

By taking part you will be able to assist the Sports Science and Medical Department the Football club refine their procedures for monitoring the training load of players. The aim of the project is to help to maximise player training and match performance and minimize incidence of injury.

Possible disadvantages/ risks in taking part.

You will perform maximal exercise tests which will require you to run at high intensities as is common within your day to day routine. There is always a slight increased risk of a cardiac event or muscle/joint injury by completing such exercise. The risks to health are minimal for those without underlying health conditions, which you will be screened for before exercising using the PAR–Q health questionnaire and be closely monitored by the Sports Science and Medical Team at the club. As a consequence of the physical exercise tests you may experience; discomfort, tiredness and feeling out of breath, but this should be minimised by a thorough warm up and cool down. Persons trained in First Aid will be present and a first aid kit and a defibrillator will be available.

Do I have to participate in the study?

Taking part in this study is completely voluntary. If you decide to participate, you will be given this information sheet to keep and be asked to sign an informed consent form. However, you can withdraw from this study at any time without giving a reason and all previous data collected will be appropriately destroyed. There will be no influence of your decision to take part or withdraw from this study on team selection.

Who has organised the study?

The study is supervised by Dr James Hopker and Dr John Dickinson from the University of Kent, and James Russell and Gary Hemens from Gillingham Football Club. Ethical approval was granted by the University of Kent Sport and Exercise Research Ethics Committee.

Will my participation be confidential?

Once you have agreed to participation, you will be asked to sign a consent form and assigned a study code that will be used on all data sheets to anonymise you. Hard copies of consent forms will be kept in a locked filing cabinet, available only to the research team, so only they are able to trace personal information to the study code. Consent forms will be kept for 12 months as a record for out ethics committee, but will be destroyed following this time. Anonymous data will be stored for up to 5 years after the study.

What will happen to the results of the study?

The findings of the study will be published in scientific journals and presented at conferences, but no individual references that will reveal your identity will be made, such that you remain completely anonymous.

Who should I contact about this study?

Meanwhile, if you have any questions about the study, participants should contact the organiser (Clement Chan – csmc4@kent.ac.uk) or the supervisor (Dr James Hopker – J.G.Hopker@kent.ac.uk). If the participant wishes to make a complaint about the study, they can contact the supervisor OR the SSES Director or Research. Dr. Glen Davison (G.Davison@Kent.ac.uk).
Thank you for your time reading this information sheet about the study of interest. If you wish to participate or you have any further questions.

Appendix B: Health Questionnaire

HEALTH QUESTIONNAIRE

Participant ID ……………………………………………………

Please answer these questions truthfully and completely. The sole purpose of this questionnaire is to ensure that you are in a fit and healthy state to complete the exercise test.

ANY INFORMATION CONTAINED HEREIN WILL BE TREATED AS CONFIDENTIAL.

SECTION 1: GENERAL HEALTH QUESTIONS

Please read the 8 questions below carefully and answer each one honestly: check YES or NO.

	YES	NO
1. Has your doctor ever said that you have a heart condition or high blood pressure?	□	□
2. Do you feel pain in your chest at rest, during your daily activities of living, or when you do physical activity?	□	□
3. Do you lose balance because of dizziness or have you lost consciousness in the last 12 months? (Please answer NO if your dizziness was associated with over-breathing including vigorous exercise).	□	□
4. Have you ever been diagnosed with another chronic medical condition (other than heart disease or high blood pressure)?	□	□
If yes, please list condition(s) here:		
5. Are you currently taking prescribed medications for a chronic medical condition?	□	□
If yes, please list condition(s) and medications here:		
6. Do you currently have (or have you had within the past 12 months) a bone, joint or soft tissue (muscle, ligament, or tendon) problem that could be made worse by becoming more physically active? Please answer NO if you had a problem in the past but it *does not limit your ability* to be physically active.	□	□
If yes, please list condition(s) here:		
7. Has your doctor ever said that you should only do medically supervised physical activity?	□	□
8. Are you, or is there any chance you could be, pregnant?	□	□

If you answered NO to all of the questions above, you are cleared to take part in the exercise test

Go to SECTION 3 to sign the form. You do not need to complete section 2.

If you answered YES to one or more of the questions in Section 1 - PLEASE GO TO SECTION 2.

SECTION 2: CHRONIC MEDICAL CONDITIONS

Please read the questions below carefully and answer each one honestly: check YES or NO.

		YES	NO
1.	**Do you have arthritis, osteoporosis, or back problems?** If YES answer questions 1a-1c. If NO go to Question 2.	☐	☐
1a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking any medications or other treatments).	☐	☐
1b.	Do you have joint problems causing pain, a recent fracture or fracture caused by osteoporosis or cancer, displaced vertebrae (e.g. spondylolisthesis), and/or spondyloysis/pars defect (a crack in the bony ring on the back of the spinal column)?	☐	☐
1c.	Have you had steroid injections or taken steroid tablets regularly for more than 3 months?	☐	☐
2.	**Do you have cancer of any kind?** If YES answer questions 2a-2b. If NO, go to Question 3.	☐	☐
2a.	Does your cancer diagnosis include any of the following types: lung/bronchogenic, multiple myeloma (cancer of plasma cells), head and neck?	☐	☐
2b.	Are you currently receiving cancer therapy (such as chemotherapy or radiotherapy)?	☐	☐
3.	**Do you have heart disease or cardiovascular disease? This includes coronary artery disease, high blood pressure, heart failure, diagnosed abnormality or heart rhythm.** If YES answer questions 3a-3e. If NO go to Question 4.	☐	☐
3a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking any medications or other treatments).	☐	☐
3b.	Do you have an irregular heartbeat that requires medical management? (e.g. atrial fibrillation, premature ventricular contraction)	☐	☐
3c.	Do you have chronic heart failure?	☐	☐
3d.	Do you have a resting blood pressure equal to or greater than 160/90mmHg with or without medication? Answer YES if you do not know your resting blood pressure.	☐	☐
3e.	Do you have diagnosed coronary artery (cardiovascular) disease and have not participated in regular physical activity in the last 2 months?	☐	☐

		YES	NO
4.	**Do you have any metabolic conditions? This includes Type 1 Diabetes, Type 2 Diabetes and Pre-Diabetes.** If YES answer questions 4a-4c. If NO, go to Question 5.	☐	☐
4a.	Is your blood sugar often above 13mmol/L? (Answer YES if you are not sure).	☐	☐
4b.	Do you have any signs or symptoms of diabetes complications such as heart or vascular disease and/or complications affecting your eyes, kidneys, OR the sensation in your toes and feet?	☐	☐
4c.	Do you have other metabolic conditions (such as thyroid disorders, current pregnancy related diabetes, chronic kidney disease, or liver problems)?	☐	☐
5.	**Do you have any mental health problems or learning difficulties?** This includes Alzheimer's, dementia, depression, anxiety disorder,	☐	☐

	eating disorder, psychotic disorder, intellectual disability and down syndrome. If YES answer questions 5a-5b. If NO go to Question 6.		
5a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking any medications or other treatments).	□	□
5b.	Do you also have back problems affecting nerves or muscles?	□	□
6.	**Do you have a respiratory disease?** This includes chronic obstructive pulmonary disease, asthma, pulmonary high blood pressure. If YES answer questions 6a-6d. If NO, go to Question 7.	□	□
6a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking any medications or other treatments).	□	□
6b.	Has your doctor ever said you blood oxygen level is low at rest or during exercise and/or that you require supplemental oxygen therapy?	□	□
6c.	If asthmatic, do you currently have symptoms of chest tightness, wheezing, laboured breathing, consistent cough (more than 2 days/week), or have you used your rescue medication more than twice in the last week?	□	□
6d.	Has your doctor ever said you have high blood pressure in the blood vessels of your lungs?	□	□
7.	**Do you have a spinal cord injury?** This includes tetraplegia and paraplegia. If YES answer questions 7a-7c. If NO, go to Question 8.	□	□
7a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking any medications or other treatments).	□	□
7b.	Do you commonly exhibit low resting blood pressure significant enough to cause dizziness, light-headedness, and/or fainting?	□	□
7c.	Has your physician indicated that you exhibit sudden bouts of high blood pressure (known as autonomic dysreflexia)?	□	□

		YES	NO
8.	**Have you had a stroke?** This includes transient ischemic attack (TIA) or cerebrovascular event. If YES answer questions 8a-8c. If NO go to Question 9.	□	□
8a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking any medications or other treatments).	□	□
8b.	Do you have any impairment in walking or mobility?	□	□
8c.	Have you experienced a stroke or impairment in nerves or muscles in the past 6 months?	□	□
9.	**Do you have any other medical condition which is not listed above or do you have two or more medical conditions?** If you have other medical conditions, answer questions 9a-9c. If NO go to Question 10.	□	□
9a.	Have you experienced a blackout, fainted, or lost consciousness as a result of a head injury within the last 12 months OR have you had a diagnosed concussion within the last 12 months?	□	□
9b.	Do you have a medical condition that is not listed (such as epilepsy, neurological conditions, and kidney problems)?	□	□
9c.	Do you currently live with two or more medical conditions?	□	□
	Please list your medical condition(s) and any related medications here:		
10.	**Have you had a viral infection in the last 2 weeks (cough, cold, sore throat, etc.)?** If YES please provide details below:	□	□
11.	**Is there any other reason why you cannot take part in this exercise test?** If YES please provide details below:	□	□
12.	**Please provide brief details of your current weekly levels of physical activity (sport, physical fitness or conditioning activities), using the following classification for exertion level:** **L = light (slightly breathless)** **M = moderate (breathless)** **V = vigorous (very breathless)** **Activity** **Duration (mins.)** **Level (L/M/V)** **Monday** **Tuesday** **Wednesday** **Thursday** **Friday** **Saturday** **Sunday**		

Please see below for recommendations for your current medical condition and sign this document:

If you answered NO to all of the follow-up questions about your medical condition, you are cleared to take part in the exercise test.

If you answered YES to one or more of the follow-up questions about your medical condition it is strongly advised that you should seek further advice from a medical professional before taking part in the exercise test.

This health questionnaire is based around the PAR-Q+, which was developed by the Canadian Society for Exercise Physiology www.csep.ca

Appendix C: Consent Form

Title of project: Investigating the effects of neuromuscular fatigue on match performance.
Name of investigators: Clement Chan, Dr. James Hopker, John Dickinson, James Russell and Gary Hemens.
Participant Identification Number for this project:

Please initial box

1. I confirm I have read and understand the information sheet dated 05/11/18 for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason. If I wish to withdraw I may contact Clement Chan (csmc4@kent.ac.uk, 07729878235). ☐

3. I understand that my responses / data will be anonymised before analysis. I give permission for members of the research team to have access to my anonymised data. ☐

4. I understand that I must read the health questionnaire carefully and answer the questions to the best of my ability, and that the researchers will use my answers to this questionnaire to assess my suitability for participation. ☐

5. I agree to take part in the above research project. ☐

________________________	________________________	________________________
Name of participant	Date	Signature
________________________	________________________	________________________
Name of person taking consent	Date	Signature
________________________	________________________	________________________
Lead researcher	Date	Signature

Appendix D: Matches of English League 1 2018/2019 Season and Player Involvement

Legends

	Not involved
45'	Subbed in at 45th minute
87'	Subbed out at 87th minute
	Uninvolved due to hamstring injury

Games	Dates	Bingham	Byrne	Cook	Eaves	Fuller	Zakuani	Garmston	Hanlan	Lacey	List	Ehmer	Navvid	O'Neill	Parker	Parrett	Rees	Reilly	Ogilvie	Oldaker	Burke	Campbell	King	Da Silva
Accrington (A) W	8/4/2018				70'				70'															
Burton (H) W	8/11/2018				33'											33'								
Millwall (A) L	8/14/2018				76'	74'		74'										64'						
Walsall (A) L	8/18/2018	67'				78'			66'					78'				67'						
Sunderland (H) L	8/22/2018	70'							85'		70'			70'				70'						
Coventry (H) D	8/25/2018		31'	41'					74'		41'							31'						
Barnsley (A) L	9/1/2018						40'		56'	40'	67'						56'							
Portsmouth (A) L	9/4/2018									80'	65'						62'							
Wimbledon (A) L	9/8/2018								46'		46'			46'			46'							
Rochdale (A) L	9/15/2018								83'		57'		71'	71'	57'	83'								
Peterborough (H) L	9/22/2018			50'	50'				83'								66'	66'						

Games	Dates	Bingham	Byrne	Cook	Eaves	Fuller	Zakuani	Garmston	Hanlan	Lacey	List	Ehmer	Navvid	O'Neill	Parker	Parrett	Rees	Reilly	Ogilvie	Oldaker	Burke	Campbell	King	Da Silva
Shrewsbury (A) D	9/29/2018				68'	55'		55'							68'	65'	65'							
Portsmouth (A) W	10/6/2018								79'		79'													
Spurs U21 (H) L	10/9/2018		46'						66'		66'					46'		46'						
Southend (H) L	10/13/2018						68'	59'		59'								59'						
Doncaster (A) D	10/20/2018	57'								57'			74'	74'					56'					
Plymouth (A) L	10/21/2018	78'						46'					69'				78'	46'						
Bradford (H) W	10/27/2018	83'		74'					66'		66'		74'			83'								
Fleetwood (H) W	11/3/2018	46'		76'					69'		69'					76'			46'					
Blackpool (H) L	11/6/2018			77'							76'			76'	88'	77'			88'					
Hartlepool (H) D	11/10/2018	46'							46'		46'								46'					
Crawley Town (H) L	11/13/2018	75'									65'		79'											
Oxford Utd (A) L	11/17/2018																							
Hartlepool (A) W	11/21/2018			64'	118'	73'		73'	46'	118'	46'						64'							
Luton Town (H) L	11/24/2018	63'						63'							61'	61'	61'			61'				
Bristol Rovers (A) W	11/27/2018	83'					15'	15'			82'			82'				70'		83'				
Slough Town (A) W	12/2/2018			80'		74'		62'			80'			74'		62'								
Scunthorpe (A) W	12/8/2018	82'								69'		69'				82'								

Games	Dates	Bingham	Byrne	Cook	Eaves	Fuller	Zakuani	Garmston	Hanlan	Lacey	List	Ehmer	Navvid	O'Neill	Parker	Parrett	Rees	Reilly	Ogilvie	Oldaker	Burke	Campbell	King	Da Silva
Wycombe (H) D	12/15/2018							46'	86'		86'									46'				
Charlton (A) L	12/22/2018			71'		66'			71'					66'				46'		46'				
Portsmouth (H) W	12/26/2018	69'							76'					76'	92'	69'								
Doncaster (H) L	12/29/2018	26'			46'	59'			46'					59'		26'								
Southend (A) L	1/1/2019	50'									84'						50'	84'						
Cardiff City (H) W	1/5/2019																							
Burton (A) W	1/12/2019			76'			89'		58'			89'					76'		58'					
Walsall (H) L	1/19/2019			46'	35'				63'	35'					46'			63'						
Swansea (A) L	1/26/2019					83'			71'		71'			83'		83'			83'					
Accrington (H) D	1/29/2019			88'							88'								88'					
Coventry (A) D	2/2/2019										71'												88'	71'
Barnsley (H) L	2/9/2019			78'							54'					65'	65'		78'				54'	
Scunthorpe (H) W	2/16/2019	63'									85'							78'		63'	85'			78'
Sunderland (A) L	2/19/2019			68'							74'					90'				74'	90'			68'
Wycombe (A) W	2/23/2019	45+1'		78'	66'											45+1'					78'	66'		
Fleetwood (A) D	3/2/2019								79'		79'													
Oxford Utd (H) W	3/9/2019			61'							78'					72'		72'			78'			61'
Bristol Rovers (H) L	3/12/2019			83'							60'									60'				83'

Games	Dates	Bingham	Byrne	Cook	Eaves	Fuller	Zakuani	Garmston	Hanlan	Lacey	List	Ehmer	Navvid	O'Neill	Parker	Parrett	Rees	Reilly	Ogilvie	Oldaker	Burke	Campbell	King	Da Silva
Luton (A) D	3/16/2019																87'							87'
Wimbledon (H) W	3/23/2019			87'					90+5'		90+5'					90+6'					87'			90+6'
Rochdale (H) D	3/30/2019			86'												90+1'	90+1'				86'			
Peterborough (A) L	4/6/2019										80'										80'		90+1'	
Shrewsbury (H) L	4/13/2019	46'									46'					73'	67'				67'	73'		
Plymouth Argyle (H) W	4/19/2019	46'		73'	46'						46'						73'					46'		
Bradford City (A) D	4/22/2019				83'	40'		40'									65'					83'		65'
Charlton (H) L	4/27/2019			65'	45'						71'					65'	71'					45'		
Blackpool (A) W	5/4/2019				87'					68'	87'							79'		79'				68'

Table 5: Matches in English League 1 Season 2018/2019 and player involvement.