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Monitoring Acute Fatigue in Soccer Players.

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Abstract

Monitoring fatigue is a key consideration when managing the workloads of elite soccer players. A number of potential fatigue markers have been proposed, however, little work has been done in order to assess the correlation between such measures and actual performance. Therefore, the objectives of this study were: (1) to examine the correlation between a range of simple fatigue tests and physical performance; and (2) to develop a model by which readiness to perform could be predicted. In order to do this 14 amateur soccer players completed a range of fatigue tests (countermovement jump, resting heart rate variability, functional soreness, and subjective wellness) and a performance test (3x 30 m repeated sprint test) before and after (24, 48, and 72 hours post) undertaking a soccer simulation protocol (Loughborough Intermittent Shuttle Test; LIST). Following the LIST repeated sprint performance and countermovement jump height, and heart rate variability were reduced, perceived soreness increased, and subjective wellness declined. Of the fatigue measures used, only countermovement jump height was found to be correlated with repeated sprint performance. Three models for predicting performance were developed which differed in their degree of individuality. Individual models were found to have a greater strength than the general model. For practitioners, more work is required to develop individual models, however, predictions made from individual models are likely to be more accurate. Future studies are needed to refine these models in order that they might be used in practice to make decisions about readiness to train and perform.

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List of Abbreviations

24h (48,72) = 24 (48,72) hours post-LIST

CK = Creatine Kinase

CMJ = Countermovement Jump

CV = Coefficient of Variance

ECG = Electrocardiograph

EPL = English Premier League

FORD = Free Oxygen Radical Defence Test

FORT = Free Oxygen Radical Test

FTG = Perceived Fatigue

FS = Functional Soreness

GM = General Model

GMS = Perceived General Muscle Soreness

GPS = Global Positioning Systems

HR = Heart Rate

HREx = Heart Rate during Exercise

HRR = Heart Rate Recovery

HRV = Heart Rate Variability

HSR = High Speed Running

IIM = Individual Intercept Model

ISM = Individual Slope Model

LIST = Loughborough Intermittent Shuttle Test

MD-1 (2,3,4) = Match Day Minus 1 (2,3,4)

OTS = Overtraining Syndrome

RHR = Resting Heart Rate

rMSSD = square root of mean sum of squares of differences between normal adjacent R-R intervals

RPE = Rating of Perceived Exertion

RSA = Repeated Sprint Ability

SAFT = Soccer-Specific Aerobic Fitness Test

s-IgA = Salivary Immunoglobulin A

SPR = Sprint Distance

SRQ = Self Report Questionnaires

T:C Ratio = Testosterone:Cortisol Ratio

URTI = Upper Respiratory Tract Infections

VO_{2MAX} = Maximal Oxygen Uptake

Yo-Yo IR1 = Yo-Yo Intermittent Recovery Test Level 1

Chapter 1: Introduction

During the preseason and competition phases of the season, elite soccer players face heavy training and competition workloads (Nedelec et al., 2012). Physical fatigue can also be compounded by mental aspects resulting from pressures such as intense match play; regular long distance travel and staying away from home; and, media and public attention (Meister et al., 2013; Nedelec et al., 2012). Decisions about a player's readiness to train or compete must be made on a daily basis (Malone, Murtagh, Morgans, Burgess, Morton, & Drust, 2015; Thorpe et al., 2015). As such, managing the balance between fatigue and recovery time is of great significance. Where extended periods of imbalance occur the result can be reduced performance and increased injury risk associated with overtraining (Urhausen & Kindermann, 2002). Conversely, imbalance in the opposite direction can result in undertraining and suboptimal conditioning (Gabbett, 2016; Gustafsson, Holmberg, & Hassmen, 2008; Malone et al., 2015). In order to correctly balance training and recovery it is necessary to monitor individual fatigue levels and to adjust training loads accordingly (Buchheit, 2014; Gabbett, 2016). The most valid test for monitoring readiness to train (or compete) would be to assess performance during a complete soccer match (90 min) (Taylor et al., 2012). However, such direct and maximal performance testing is clearly counterproductive because of the extra fatigue it would impose, the risk of injury, and the time taken to perform the measurement. Furthermore, in the case of team sports, there is also no objective way to measure individual performance as there is with some individual sports (e.g. race times or throw/jump distances). Therefore there is a need for valid and sensitive fatigue markers, which can provide information on a player's readiness to perform, without imposing any further fatigue (McCall et al., 2015).

The monitoring of fatigue can become more difficult in the international soccer context. In comparison to domestic club environments, international soccer teams face a unique set of challenges in that: (1) they will generally only have access to their players for short periods at a time; (2) the team will often be playing overseas and will not have access to sophisticated equipment required for some monitoring protocols (e.g. biochemical measures); and (3) their players will often arrive in varying states of fatigue, from playing for their respective clubs, and having flown across a number of time zones. In such situations coaches and sports scientists also require some means of determining the fatigue levels and readiness to train of players. The tests used to determine this must be simple to administer, non-exhaustive for the players, and must be able to be completed easily (e.g. in a hotel) without access to laboratory equipment. As such this study has focused on simple, non-fatiguing, and non-invasive monitoring tests.

Early research attempting to monitor responses to training using fatigue markers focused predominantly on individual sports (e.g. cycling, triathlon), however, recently a large number of such studies have been conducted within team sports (Buchheit et al., 2013; Clarke, Farthing, Lanovaz, & Krentz, 2015; Malone et al., 2015; McLean, Coutts, Kelly, McGuigan, & Cormack, 2010; Thorpe et al., 2015). Research has yet to identify a single fatigue marker which can accurately reflect readiness to train, and it would seem that finding such a simple solution is unlikely due to the multi-disciplinary nature of fatigue (Buchheit et al., 2014; Nedelec et al., 2012). Therefore, practitioners in elite team (and individual) sport often use a mixed-methods approach when monitoring players' responses to training loads (Meister et al., 2013; Saw, Main, & Gatin, 2015a; Taylor et al., 2012). Measures that have been included in such approaches can be categorised as either physiological (e.g. heart rate variability), biochemical (e.g. cortisol:testosterone ratio), neuromuscular (e.g. vertical jump height), or perceptual (e.g. subjective well-being questionnaires).

Among physiological measures, heart rate parameters that have been indicated as potential fatigue markers include heart rate (HR) and heart rate variability (HRV), and these measures have been taken either at rest, during exercise, or during recovery after exercise (Buchheit et al., 2014). Of these variants, resting HRV has been suggested as the most applicable heart rate measure of fatigue (Buchheit et al., 2014; Flatt & Esco, 2013; Plews et al., 2013). HRV is a measure of the change in the time gap between heart beats, which is a marker of autonomic nervous system status, in particular parasympathetic reactivation towards homeostasis (Stanley et al., 2013). HRV was reduced in a fatigued state following a period of overload training and recovered when the training load was reduced (Plews et al., 2013). The specific measurement of HRV recommended by existing literature is a morning measurement using the square root of mean sum of squares of differences between normal adjacent R-R intervals (rMSSD). The popularity of rMSSD is a result of its improved sensitivity of physical and non-physical stressors; reduced compounding factors in the measurement (e.g. respiratory rate); and the short length of recording required. In comparison to some lab-based tests, measuring HRV has become relatively inexpensive and non-invasive (Buchheit, 2014) particularly since the development of smart-phone applications. One such application (ithlete; HRV Fit Ltd. Southampton, UK) has been validated against a traditional electrocardiograph HRV measurement and found to be in near perfect agreement following a 60-s recording (Flatt & Esco, 2013).

Jump tests are often used to monitor neuromuscular fatigue (Taylor et al., 2012). Countermovement jumps (CMJ) appear to be the most popular choice because they incorporate the stretch-shortening cycle of the muscle (Gathercole, Stellingwerff, & Sporer, 2015; McLean, Petrucelli, & Coyle, 2012; Nedelec et al., 2012; Taylor et al., 2012). CMJ has previously been used as a fatigue marker in soccer with male (Meister et al., 2013), female (McLean et al., 2012), and youth players (Malone et al.,

2015). There are a number of methods used to assess CMJ, which differ in regards to their ease of use in a field setting (e.g. international team staying in a hotel). The gold standard measure would be taken on a force platform but more transportable tools include contact mats, 'Vertecs', or, more recently, smartphone applications (Balsalobre-Fernandez, Glaister, & Lockett, 2015).

Subjective wellness assessments, or self-report questionnaires (SRQs) are the most widely used fatigue measure in high performance sport (Taylor et al., 2012). The simplicity of SRQs allows them to be widely used and technological development is rapidly moving these assessments from paper-and-pen methods, to smartphones and web-based servers (Saw, Main, & Gustin, 2015b). A recent review found subjective wellness assessments to be more closely related to fluctuations in training loads than objective measures (Saw et al., 2015a). Similar conclusions were drawn by Thorpe et al. (2015) who monitored Premier League soccer players in England.

Although there has been a plethora research into fatigue measures, the focus of the majority of studies has been the sensitivity of selected measures to detect changes in fatigue and reflect variations in training loads (Saw et al., 2015a; Thorpe et al., 2015; Malone et al., 2015). This work has been, and remains, highly necessary in order to determine the most valid, sensitive, and practical fatigue measures. A progression from this work though, is to correlate fatigue measures with performance, and then use fatigue measures to model and predict performance. To the author's knowledge only one study has attempted to correlate fatigue measures with actual performance (Buchheit et al., 2013) and no study has attempted to model the relationship between fatigue and performance such that predictions of performance could be made from fatigue data. Therefore, the objectives of this study were to examine the correlation between a range of simple fatigue tests and physical performance, and subsequently develop a model to predict readiness to perform. For the purposes of this study the selected physical performance measure was a short repeated sprint ability (RSA) protocol, as RSA has previously been correlated with between-player differences in physical output during soccer matches (Carling et al., 2012; Rampinini et al., 2007).

1.1 Hypothesis

1. RSA, CMJ, HRV, and subjective wellness will be reduced, while soreness will be increased, in recreational male soccer players following the soccer simulation.
2. Subjective wellness assessments will show the strongest correlation with change in RSA performance.

Chapter 2: Literature Review

2.1 Introduction

2.1.1 Physical Demands of Elite Soccer

Performance in soccer is comprised of factors from technical, tactical, mental, and physiological domains (Ekblom, 1986; Stolen, Chamari, Castagna, & Wisloff, 2005). Even from a purely physiological perspective, performance is multifaceted with high-level soccer requiring qualities such as cardiovascular endurance, muscular endurance, speed, strength, power, agility, and flexibility (Morgans, Orme, Anderson, & Drust, 2014). Soccer stresses both the aerobic and anaerobic systems as brief bouts of intense activity are interspersed by periods of lower intensity recovery (Anderson et al., 2016; Barnes, Archer, Hogg, Bush, & Bradley, 2014; Morgans et al., 2014).

Outfield players generally cover between 10-12 km during a 90 min game, with the game played at an average of 80-90% of a player's maximum heart rate (Stolen et al., 2005). Elite soccer players perform a sprinting action every 90 s with the average sprint duration being between 2-4 s (Bangsbo, Norregaard, & Thorso, 1991). These sprinting actions have been suggested to make up approximately 8-18% of the total distance covered during match-play (Ekblom, 1986). In addition to running, soccer-specific activities are performed during match play with the average game including approximately 15 tackles, 10 headers, 50 ball interactions, and 30 passes per player (Stolen et al., 2005). The above statistics have been accepted and cited for years however, a recent update found that physical performance in the English Premier League (EPL) is evolving. While total distance stayed fairly constant, high-intensity running distance and sprint distance increased by 30-35% between the 2006-07 and 2012-13 seasons (Barnes et al., 2014). Players in the modern game were found to make shorter, but more frequent and explosive, sprint efforts (Barnes et al., 2014). Powerful actions like explosive sprints and changes of direction have been associated with pivotal moments which decide match outcome showing the importance of speed and power attributes for soccer performance (Morgans et al., 2014; Stolen et al., 2005). These changes may reflect the development of physical capabilities of elite players and changes in the tactical approach to the modern game. Interestingly, there was a significant increase in high intensity running when out of ball possession, over the seven seasons monitored (451 m in 2006-07 to 589 m in 2012-13), which might reflect an increased focus on high pressure defending (or 'pressing') by the team without the ball.

In addition to the demands of game play, it is important that the demands of all training sessions are included when quantifying the weekly workload of a soccer player (Anderson et al., 2016). Due to the multi-dimensional nature of soccer performance the training activities carried out can be diverse (Morgans et al., 2014). A weekly microcycle may include several modes of training such as technical drills, tactical work, aerobic and lactate threshold conditioning, speed and agility exercises, gym-based resistance training, as well as injury prevention exercises and recovery sessions.

Quantifying and managing training loads is a key concern for sports scientists working in elite soccer (Buchheit, 2014). Both 'external' (the absolute load of a session often measured in distance covered at varying intensities) and 'internal' (the relative load an individual is placed under by the external load often measured using RPE or heart rate measures) loads should be measured. External training load is commonly monitored in the professional game using global positioning systems (GPS) technology. In-season training session durations are often between 50-70 min (Anderson et al., 2016). During such sessions players have been reported to cover between 3500-6500 m total distance with 75-300 m at high intensity ($>19.8 \text{ km}\cdot\text{h}^{-1}$) (Guadino et al., 2013; Malone et al., 2015). External training loads are often greatest during preseason and reduce as the season progresses (Malone et al., 2015). There is also periodisation within the weekly microcycle with sessions constituting vastly different external loads. The range of total distance covered during elite soccer trainings within one team ranged from approximately 1500-5200 m and high speed running from 0 - 100 m (Anderson et al., 2016). The cumulative weekly external load is highly dependent on the number of games played with a 3-game week (i.e. 3 games played within a 7-day period) resulting in greater total distance, high speed running distance, and sprint distance ($>25.2 \text{ km}\cdot\text{h}^{-1}$) than a 2-game week, during which players accrued higher loads across all metrics than during a 1-game week (Anderson et al., 2016). Total distance covered during the weeks was 26, 32, and 36 km for 1-, 2-, and 3-game weeks, respectively (Anderson et al., 2016). When viewed over an entire season match involvement (or player 'starting status') also affects external load with regular starters covering more high intensity and sprinting distance than non-starters, and more sprinting distance than fringe players (i.e. occasional starters), despite total distance being similar across the three groups (Anderson et al., 2016b).

Internal loads reflects the physiological strain placed on an individual player, by a given external load (Kelly, Strudwick, Atkinson, Drust, & Gregson, 2016). The predominant means of quantifying internal load is session-RPE. Session-RPE is calculated by multiplying the duration of the session (in minutes) by the RPE score attributed to that session by each individual on Borg's category ratio scale (CR10) (Brito, Hertzog, & Nassis, 2016). Weekly training loads of between 1800-2500 arbitrary units (au)

have been reported for elite youth players (Brito et al., 2016), while a single in-season session load was between 220-410 au among a sample of EPL players (Malone et al., 2015).

The workloads elicited by elite soccer competition and training, and means of measuring the workload, have now been outlined. In order to appropriately manage workloads it is necessary to assess players' individual response to the workload (i.e. monitor fatigue levels). This concept will be expanded on in the following section.

2.1.2 Why Monitor Fatigue in Elite Soccer?

The balance between training load and recovery is vital for maintaining and improving performance. While overreaching can be planned in to a periodised training programme, long-term imbalance can result in reduced performance, increased injury risk, and eventually over training syndrome (OTS) (Buchheit, 2014; Gabbett, 2016; Gustafsson et al., 2008). Similarly, tapering or 'de-loading' are necessary parts of a programme but insufficient training stimuli, if prolonged, will result in suboptimal conditioning (Buchheit, 2014; Gabbett, 2016; Gustafsson et al., 2008; Nedelec et al., 2012). Monitoring an individual's response to training is therefore useful as it provides feedback on the training load they are under. This feedback enables one of three courses of action: (1) continue current training load; (2) further investigate training load; (3) modify training load (Gabbett, 2016).

Regular monitoring of individual fatigue levels is a key consideration in elite soccer where competitive fixtures occur once, and often twice, a week for most of the year (Anderson et al., 2016; Nedelec et al., 2012). Indeed fixture scheduling can become so congested that teams can play 5 games in 15 days (Morgans, Orme, Anderson, Drust, & Morton, 2014). Not only do players need to be available for matches, but decisions on their readiness to train need to be made on a daily basis (Thorpe et al., 2015). Compounding the physical stressors is the mental component of fatigue which results from factors such as long distance travel, time away from home and family, disturbed sleep patterns, and media and public scrutiny (Meister et al., 2013; Nedelec et al., 2012). As such, monitoring in soccer is not about detecting OTS but about managing multifaceted fatigue (via training recovery balance) on a weekly basis to ensure players are in optimal condition for as many matches as possible throughout the season.

Therefore, the ideal fatigue marker would be sensitive to subtle changes in readiness to train, simple to measure with a quick turnaround time, able to reflect the multifaceted nature of fatigue development, and related to soccer performance. Given that there is no gold standard fatigue test that meets all these criteria, most researchers suggest that multiple measures are taken in order to 'triangulate' a player's fatigue state (Gustafsson et al., 2008; Lewis et al., 2016; Meister et al., 2013).

Such an approach is generally referred to as multidimensional monitoring (Meister et al., 2013). The value of successful monitoring, optimally conditioned players, and reduced injuries cannot be overstated. Having more players available for more matches over a season has been directly associated with success in elite soccer (Eirale, 2013; Hagglund, 2013).

2.1.3 International Soccer

International soccer teams face a unique set of challenges when compared with domestic teams (McCall et al., 2015a; Morgans et al., 2015). Interestingly, higher injury rates have been reported at World Cup events than in domestic club settings (McCall et al., 2015a). Suggested reasons for this phenomenon include: accumulated fatigue from club environments; limited information on player condition provided by clubs; sudden changes in training style; congested fixtures in tournament format; unfamiliar climate; repeated travel; limited recovery facilities; and the highly competitive nature of World Cup games (McCall et al., 2015a). These reasons provide an insight into the challenges faced by national team sports science and medical departments.

The transition from club to international soccer (and vice versa) can be smoothed by effective sharing of information between the respective sports science departments (McCall et al., 2015a); particularly the 'feedforward' of information from club to country prior to international activity, and the 'feedback' of information to club from country following international activity. This has previously been recommended for the transition between domestic and international rugby union teams (Cunnliffe et al., 2011). This exchange of information was also the subject of a recent article (Wallace, 2016) in an English newspaper as EPL teams agreed for the first time to share sports science and medical information with the national team to assist in their preparations for the 2016 European Championship in France.

When national teams gather it will be for one of two main types of activity, either a standard Fédération Internationale de Football Association (FIFA) international window (a period of approximately 10 days during which elite domestic soccer ceases and international soccer matches occur) in which one or two fixtures will generally be played, or, for officially sanctioned tournament soccer (e.g. FIFA World Cup). In the case of standard FIFA windows players will generally arrive 4-5 days before the first game providing coaching staff minimal time to prepare the team tactically and physically for the fixture (Morgans et al., 2015). In addition to this the players will arrive in a variety of fatigue states based upon their recent minutes played, recent training load at their club, injury history, and distance travelled and time zones crossed to join the group (McCall et al., 2015a). Bearing all this in mind, decisions must be made about how to tailor the workloads of each player in order to have everyone in top condition for the match (Morgans et al., 2015). Given that players may

have spent an extensive period at their clubs playing in vastly different tactical systems, tension can also arise between the need to spend time on the field preparing the team tactically for the game, and the need to ensure they are rested and fresh for the fixture. Communication and trust between sports science or medical staff, and coaching staff is therefore hugely important in the international soccer setting (McCall et al., 2015a).

Players' journeys to join the national team can compound fatigue that athletes are already under (Nedelec et al., 2012). Often players will fly out the night after their last club game, in a state of post-game fatigue, to arrive as early as possible in the international window. Depending on the distance travelled, the direction travelled (and the class travelled i.e. economy or business) players will likely arrive to some degree dehydrated from the dry cabin environment, sleep deprived, mentally fatigued, and jet-lagged (Fowler, 2015). In such a state, intermittent running performance has been shown to be reduced (Fowler, Duffield, & Vaile, 2015). It has been suggested that to adapt to a new time zone takes half a day per time zone crossed if travelling west, and a full day per time zone if travelling east (Fowler, 2015). Therefore a player that travels westwards across 8 time zones (for example from Auckland to Dubai) would in theory need 8 days to adjust but may be required to play within 4 days of arriving.

A further issue for national soccer teams is access to monitoring equipment while playing overseas. In these circumstances any fatigue measures which require access to laboratory equipment, for either their collection or analysis, are effectively ruled out. However, advancing technologies, including point-of-care biochemical tests, are making this less of a barrier (Lewis, Newell, Burden, Howatson, & Pedlar, 2016).

2.2 Simulating Soccer Fatigue

In order to study fatigue markers athletes need to have undertaken fatiguing activity. The principle of specificity requires that the fatiguing activity be as similar as possible to the type of fatigue routinely encountered by the population in question. Therefore, in the case of soccer players, this fatigue should be related to match or training demands, which have been outlined above. In addition to the physical demands, the ideal protocol simulating soccer fatigue would also include mental fatigue aspects along with travel fatigue and jet lag. Obviously it is difficult for a single study to meet all of these criteria, but some excellent work on fatigue measures has been carried out within top EPL teams (Malone et al., 2015; Thorpe et al., 2015). These studies had little need to simulate soccer fatigue as they monitored players during their regular training and match schedules. Such study designs obviously carry a high degree of ecological validity. If such an approach is not possible, as is often the case, soccer fatigue must be generated through some artificial means and there are various ways of doing this each with their own advantages and disadvantages.

Team-sport running demands have previously been simulated using an intermittent running protocol on a non-motorised treadmill (Sirotic & Coutts, 2008). Nedelec et al. (2013) adapted this protocol to make it specific to the running demands of elite soccer. Their test was made up of two 45-min halves involving 3 and 6 s sprint periods, 3-20 s fast running periods, 3-25 s running periods, jogging periods lasting 10-40 s, and walking for periods of 5-14s, with a total of 493 activity changes during the 90 min test (Nedelec et al., 2013). Physiological markers (mean heart rate, blood lactate, and body mass loss) during and after the test were similar to those reported for match play (Nedelec et al., 2013). However, the test resulted in less of a decrement in sprint and repeated sprint times, squat jump height, and peak isometric force production than have been reported following match play (Ispiridis et al., 2009; Magalhaes et al., 2010) and field-based running protocols (Bailey et al., 2007; Ingram et al., 2007). The absence of key activities that occur during soccer play, such as changes of direction, accelerations and decelerations, were hypothesised as the reason for the reduced decrements in physical performance following the test (Nedelec et al., 2013).

Field-based soccer simulation protocols have also been developed including the Loughborough Intermittent Shuttle Test (LIST; Nicholas, Nuttall & Williams, 2000) and the Soccer-specific Aerobic Field Test (SAFT; Lovell, Knapper & Small, 2008). The LIST is a 90 min running protocol, which has been used extensively in the literature and has been previously described by Nicholas et al. (2000). In brief, the test involves 6 x 15-min blocks of intermittent exercise interspersed by 3-min rest periods. Each block involves running between two lines 20 m apart at various speeds as indicated by an audio recording. The total distance covered, the number of sprints and turns made, have been

found to be comparable between the LIST and competitive match play (Nicholas et al., 2000). Furthermore, when compared directly, the impact of the LIST on muscle damage markers and neuromuscular performance was similar to that of a friendly soccer match (Magalhaes et al., 2010).

Although it does require decelerations and changes of direction, the LIST does not replicate all soccer activities such as jumping, ball striking, and tackling (Nicholas et al., 2000). Any soccer running protocol will also struggle to replicate the mental side of fatigue as players are not required to make decisions, play under pressure, and deal with match outcome, as they are in competitive match play (Nedelec et al., 2013). Without reproducing full soccer trainings or matches it is difficult to include these aspects in a controlled test. Creating a 'friendly' match or training session in order to elicit soccer fatigue is an option, however such a study design would require a homogenous study group with regard to playing ability. Given the vast inter-individual differences in high intensity running that occur during match play, this would result in uncontrolled external workloads, particularly in a non-competitive match where there is no real motivation for players to compete to the best of their ability (Nedelec et al., 2013). Furthermore, any mental fatigue generated from a 'friendly' fixture would likely be of a lesser magnitude than experienced by elite players during and after competitive games (Nedelec et al., 2013).

2.3 Fatigue Markers

Fatigue monitoring is highly prevalent in elite sport. Taylor et al. (2012) surveyed sports science departments from a range of high performance contexts across Australia and New Zealand and of their 55 respondents, only 5 were not employing some form of monitoring. It must be noted that potentially a higher proportion of the 45 non-respondents did not have a monitoring process in place, and this may have contributed to their non-response. Furthermore, of the 50 respondents who had a monitoring system in place, 20% said it was purely to monitoring training loads, meaning that only 40 of the 55 survey respondents actually monitored fatigue levels. It is likely that this proportion has increased in recent years. At the 2014 FIFA World Cup in Brazil all 32 participating teams used some form of monitoring protocol, and 30 teams took it further by creating individual player risk profiles based on their monitoring and screening processes (McCall et al., 2015a).

Investigations into the monitoring protocols used within high performance sport have revealed a wide range of monitoring strategies (McCall et al., 2015a; McCall et al., 2015b; Taylor et al., 2012). Generally, the measures taken can be categorised as either physiological, biochemical, perceptual, or performance based. Measures within each of these categories will be examined in regards to their current use, the theory and evidence behind their use, and their applicability to elite domestic and international soccer teams.

2.3.1 Physiological

Physiological fatigue markers predominantly revolve around HR measures. The cardiovascular system plays a significant role in recovery and the restoration of homeostasis within the body. Important recovery processes such as thermoregulation, the delivery of nutrients, and the removal of by-products, are mediated by the circulatory system. As such, HR measures can provide insight into the cardiac component of recovery (Stanley, Peake, & Buchheit, 2013). HR parameters that have been indicated as potential fatigue markers include resting heart rate (RHR) (Lac & Maso, 2004), heart rate during exercise (HRex) (Buchheit et al., 2013), heart rate recovery post exercise (HRR) (Thorpe et al., 2015), and heart rate variability (HRV) taken either at rest (Flatt & Esco, 2016), during exercise (Al Haddad, Laursen, Chollet, Ahmaidi, & Buchheit, 2011), or during recovery (Buchheit et al., 2013). Although thoroughly researched, HR measures appear to be less commonly used in the field than other fatigue measures (McCall et al., 2015b; McCall et al., 2015c; Taylor et al., 2012).

2.3.1.1 Heart Rate

Measuring HR is a relatively simple non-invasive procedure which provides an objective measure of cardiac stress (Buchheit, 2014; Stanley et al., 2013). Resting heart rate has long been associated with an athlete's physiological condition with elevated RHR indicating a fatigued state (Lac & Masco, 2004). An increased RHR was one of the earliest identified signs of overtraining (Plews et al., 2012). Heart rate is influenced by a host of factors and therefore RHR measures are best taken in the morning immediately after waking in order to minimise the influence of these external factors (Buchheit, 2014).

When measuring HR_{ex} the intensity of the exercise is a key factor. A minimum of 3-4 min of exercise is required to reach steady state HR (Buchheit, 2014). Most protocols use a steady state submaximal exercise period lasting around 5 min with HR averaged over the last 30-60 s of the exercise period (Buchheit, 2014). Obviously, the exercise protocol chosen must be identical each time testing occurs. Changes in HR_{ex} may be more powerful in examining longer-term changes in cardiovascular fitness than in determining acute fatigue (Buchheit, 2014). However, when monitoring HR along with other physiological and psychological variables during a week-long soccer training camp at altitude with youth players, increased HR during submaximal exercise was the best predictor of sickness the following day (Buchheit et al., 2013).

Heart rate recovery assesses the recovery of heart rate following a period of steady state exercise. It may be measured using indices such as the number of heart beats recovered in the first minute post exercise (Al Haddad et al., 2011). The HRR measure is thought to provide insight into parasympathetic function with greater parasympathetic activity being associated with a more favourable recovery state and improved readiness to train (Al Haddad et al., 2011). This is detected by quicker HRR, while delayed HRR suggests fatigue. However, Buchheit (2014) suggested that HRR, as with HR_{ex}, is better suited to detect improvements in cardiovascular fitness than to detect acute fatigue.

It has been suggested that changes in a particular measure are only of significance when they are of a greater magnitude than half the coefficient of variation (CV) of that measure; this has been deemed the smallest worthwhile change (Hopkins, Hawley, & Burke, 1999). Therefore, the smaller the CV and the greater the sensitivity of the measure the better the ability to detect meaningful change. HRR indices were found to have a CV between 15-32% for moderated trained young athletes by Al Haddad et al. (2011). Although the authors found little difference in the CV of HRR following submaximal, or supramaximal exercise, they recommended HRR be measured following

submaximal exercise as it is associated with greater signal stability and is more easily incorporated into an athlete's training programme (Al Haddad et al., 2011).

2.3.1.2 Heart Rate Variability

In 1996 the European Society of Cardiology and the North American Society of Pacing and Electrophysiology described HRV as a promising marker of autonomic activity and attempted to standardise its measurement, interpretation, and clinical use moving forward. Since then HRV has been extensively researched in the field of sport and exercise as a more sophisticated derivative of heart rate monitoring (Plews et al., 2012). HRV is a measure of the change in the time gap between heart beats (see Figure 2.1), which is a marker of autonomic nervous system status, in particular parasympathetic reactivation towards homeostasis (Stanley et al., 2013). On the whole, positive adaptation to training is indicated by an increase in HRV, whereas a reduction in HRV suggests fatigue. An acute bout of intense exercise will generally lower HRV for 24-48 hours (Buchheit, 2014). Increased training loads over longer periods can also bring about reductions in HRV which are generally reversed when the training stimulus is reduced. Pichot et al. (2000) found a 38% fall in HRV following 3 weeks overload training which was reversed following one 'de-load' week (40% reduction in training load).

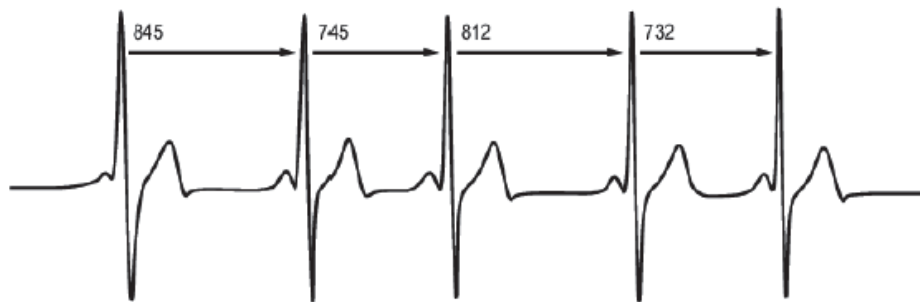


Figure 2.1 – Example of a heart rate variability graph. The arrows indicate beat to beat (R-R) intervals (duration ms).

HRV can be assessed at different states (e.g. at rest, or during exercise, or recovery), in different postures (e.g. supine, seated, or standing), and different indices can be measured (e.g. time or frequency domain indices) (Buchheit, 2014). The means of measurement chosen will have bearing on the practicality of the data collection process and the reliability of the data. In regards to the indices measured time domain metrics such as the square root of mean sum of squares of differences between normal adjacent R-R intervals (rMSSD) are now strongly recommended for a number of reasons (Buchheit, 2014; Thorpe et al., 2015). Firstly, time domain indices of HRV have been found to be less influenced by respiratory rate than frequency domain scales (Pentilla et al.,

2001). Such measures also only require a short HR recording of 10-60 s which is highly practical for field work and the measure can be simply calculated using Excel (Buchheit, 2014). Furthermore, time indices have a lower CV (~12%) than frequency indices (~82%) (Al Haddad et al., 2011). Time domain HRV measures are also reportedly responsive to both physical and non-physical stressors which is of interest in elite sport where mental fatigue is a major factor (Flatt & Esco, 2013). Concerns about the practicality of consistently implementing HRV monitoring during or post exercise in team sport settings has led to preference for a morning resting measure (Buchheit, 2014; Flatt & Esco, 2013 & 2016). Specifically, in order to achieve optimal exercise intensity for HRV measures which is below the first ventilatory threshold, the intensity may need to be individualised (Buchheit, 2014). This would require each player to be tested individually which would be a time-consuming process. Another factor inhibiting HRV monitoring during exercise is the 'noise' which is created on the recording by movement of the HR strap. This can be removed retrospectively but again is time consuming (Buchheit, 2014).

These considerations have led to many considering time domain indices of HRV, taken at rest in the morning, to be the optimal HRV measure (Buchheit, 2014; Flatt & Esco, 2013 & 2016). This measure can now be taken and analysed directly using a smart phone application (Flatt & Esco, 2013). rMSSD from a 60 s HR recording using the *ithlete* application (HRV Fit Ltd. Southampton, UK) was directly compared against an electrocardiograph (ECG) taken concurrently and found to have a near perfect agreement ($r=0.99$, $p<0.01$) (Flatt & Esco, 2013). The same technology has subsequently been used to track changes in HRV over a 5-week conditioning programme with a collegiate female soccer team (Flatt & Esco, 2016). The authors found that change in a player's HRV CV may be more predictive of the athlete's condition than the absolute changes in HRV. A very large correlation was found between change in HRV CV and change in Yo-Yo IR1 performance (pre and post the 5-week programme). In their conclusions the authors (Flatt & Esco 2016) concurred with the recent recommendations (Le Meur et al., 2013; Plews et al., 2013) to move away from looking at isolated daily measures of HRV and instead examining weekly averages and changes in intra-individual variation.

2.3.1.3 Practicalities of HR Measures for Elite Soccer

Recent surveys have indicated that HR measures are not among those commonly used for fatigue monitoring in the field with elite athletes, particularly in soccer (McCall et al., 2015b; McCall et al., 2015c; Taylor et al., 2012). This may be due to equivocal research findings, and/or the complications involved with regular HR monitoring (Buchheit, 2014). One study has reported daily HRV monitoring with EPL players (Thorpe et al., 2015) and found it weakly correlated ($r = -0.24$, $p = 0.04$) with

changes to the previous day's total high intensity running distance. If HR measures are to be monitored with elite soccer players, the most appropriate marker would appear to be a resting morning measure of rMSSD. However, the recommendations to examine HRV weekly average and CV, suggest the measure may be more useful as a chronic gauge of adaptation to the training load, and less useful as a daily measure of acute fatigue.

2.3.2 Biological

Biological markers, another category of potential fatigue tests, include those taken from blood (e.g. lactate), urine (e.g. uric acid), or saliva (e.g. immunoglobulin A or IgA). Most of these measures have been extensively researched (Lac & Maso, 2004; Petibois, Cazorla, Poortmans, & Deleris, 2002). Despite this, only 4 of 55 respondents from high performance sports science departments reported using biological measures as part of their athlete monitoring (Taylor et al., 2012). However, 16 of the 32 teams at the 2014 FIFA World Cup reported taking some form of biochemical measure as part of their monitoring process (McCall et al, 2015a). Larger budgets, more medical staff, and greater access to players, may have resulted in the increased proportion of teams at the FIFA World Cup using biochemical measures compared to those surveyed around Australia and New Zealand by Taylor et al. (2012). Also, advancements in technology in the years between the two surveys may have made biochemical measurements simpler to analyse outside of a laboratory setting (Lewis et al., 2016).

2.3.2.1 Biochemical markers

Blood lactate responses to submaximal and maximal exercise have long been used as a marker of overtraining (Bosquet, Leger, & Legros, 2001; Lac & Maso, 2004; Urhausen, Gabriel, & Kindermann, 1995). However, the use of blood lactate is not without difficulty since both optimal training and overtraining result in right shifts of the lactate curve (Bosquet et al., 2001). Although blood lactate concentrations during submaximal exercise have been used to predict time to exhaustion performance of cyclists (Sassi, Marcora, Rampinini, Mognoni, & Impellizzeri, 2006), the relevance of endurance cycling performance to soccer-specific physical performance is limited. Another potential biochemical measure is creatine kinase (CK), which 'leaks' from muscle fibres into blood plasma and can therefore, when elevated, be seen as a marker of muscle damage (Lac & Maso, 2004; Nedelec et al., 2012; Urhausen, Gabriel, & Kindermann, 1995). CK levels can be dramatically elevated post-match with the degree of elevation previously being correlated with number of sprints performed during a soccer match (Thorpe & Sunderland, 2012) and number of collisions during a rugby union match (Cunnliffe et al., 2011). However, elite players who train daily have high resting CK values making the establishment of true baseline values difficult (Nedelec et al., 2012). Furthermore, the invasive nature of blood sampling, along with the time and expertise required to take and analyse the measure, and the other factors which can create variation (e.g. nutrition), limit the usefulness of blood parameters such as lactate and CK in the day-to-day monitoring of players' fatigue levels (Buchheit, 2014).

2.3.2.2 Hormonal markers

Cortisol, testosterone, and the ratio between the two, have drawn the most attention as potential hormonal fatigue markers (Lac & Maso, 2004; Michailidis, 2014). Commonly known as the 'stress' hormone, cortisol is thought to represent the catabolic arm of metabolism, whereas testosterone is a marker of anabolic activity (Lac & Maso, 2004). The testosterone:cortisol (T:C) ratio is therefore reported to represent anabolic/catabolic balance within an individual (Urhausen, Gabriel, & Kindermann, 1995). Cortisol is raised following exercise, for example a 78% increase in concentration has previously been reported following a soccer match (Thorpe & Sunderland, 2012). Previously, a fall in the T:C ratio of greater than 30% was suggested as a marker of overtraining (Adlercreutz et al., 1986). Michailidis (2014) measured T:C ratio over a season with top-level Greek soccer players and found a reduction in the ratio (24%) between the start of the season and the halfway point in the season. This reduction was largely due to an increased concentration of cortisol, which the author hypothesised resulted from increased physiological and psychological stress at this key stage of the season (Michailidis, 2014). However, Silva et al. (2014) found opposite hormonal kinetics (increased T:C ratio and reduced cortisol levels during competitive phase) during a season with a professional soccer team playing in the Portuguese league. Moreover cortisol may also be affected by match importance, with pre-match salivary cortisol reported as being greater prior to a volleyball final than a game during the regular season (Moreira et al., 2015) whilst testosterone has been shown to be reduced by heavy endurance training loads (Lac & Maso, 2004; Urhausen, Gabriel, & Kindermann, 1995) further complicating the T:C ratio. The equivocal findings reported above, along with the difficulties associated with collecting the samples, limit the usefulness of hormonal measures as a regular part of fatigue monitoring in elite soccer.

2.3.2.3 Immunological

Under fatigued conditions immune defences can become compromised and the likelihood of developing an infection may increase. While moderate exercise is thought to stimulate the immune system, exhaustive exercise can suppress it, particularly when the physical stress is accompanied by non-physical stressors (Piggott, Newton, & McGuigan, 2009; Putlur et al., 2004). A compromised immune system is more prone to upper respiratory tract infections (URTI). One marker of immune defense which has been extensively researched in the field is salivary immunoglobulin A (s-IgA) concentration (Lac & Maso, 2004; Morgans et al., 2014b; Morgans et al., 2015; Putlur et al., 2004). s-IgA represents the body's first line of defence and primarily opposes URTI making it a good marker for susceptibility to infection among athletes (Lac & Maso, 2004). Putlur et al. (2004) found that 82%

of episodes of illness over a 9-week training period with female soccer players could be accounted for by a preceding fall in s-IgA levels.

Salivary IgA concentrations can be reduced following soccer training sessions in a dose-response manner, with high intensity sessions (greater high intensity running distance and RPE) resulting in a greater decrement than lower intensity sessions (Owen et al., 2014). A congested winter fixture schedule in the EPL has been shown to reduce s-IgA concentrations, which returned towards baseline when the schedule returned to one game per week (Morgans et al., 2014b). This is of particular concern as the winter climate in the UK will independently increase the likelihood of infections (Orhant, Carling, & Cox, 2010). These reductions in s-IgA were present even among those players who played less than half of the match minutes available during the study period, suggesting that factors other than game time alone (such as regular travel, cold weather, psychological pressure) may have led to the fall in immunity (Morgans et al., 2014b). Further evidence for the impact of non-physical stressors on s-IgA concentrations is the reduced levels found prior to matches of high importance (Moreira et al., 2013).

Salivary IgA is a simple, non-invasive measure that can be taken in the field using a saliva swab. Technological advancements mean it can now be analysed at the point of care, without required laboratory equipment (Morgans et al., 2014b), making it a viable option for travelling international teams (Morgans et al., 2015). In the international context Morgans et al. (2015) monitored s-IgA of an international squad in the 4 days leading up to 7 games during qualifying for the 2014 FIFA World Cup. The average s-IgA was significantly lower on match day minus 1 (MD-1) when compared to MD-3 and MD-4 suggesting that the training load during the camp had progressively lowered immunity; unfortunately the study did not report training loads (Morgans et al., 2015). Given the findings of Moreira et al. (2013) on the influence of match importance on s-IgA concentrations, it could be proposed that psychological stress of the upcoming qualifying match contributed to the fall in s-IgA concentrations. From this perspective it would be interesting to see the concentrations on the match day itself, however, these were not measured, presumably out of an understandable desire to allow players to undertake their normal match-day preparations.

Oxidative stress is another category of immunity markers that has been researched with relevance to fatigue and recovery balance (Lewis et al., 2016). Elevated mitochondrial oxygen consumption during a soccer match and the inflammatory response post game together result in an increased production of reactive oxygen species, which in turn increases oxidative stress within the body (Nedelec et al., 2012). One marker of redox state is uric acid, which can be increased by 0-75% post game for up to 96 hours (Nedelec et al., 2012), although Silva et al. (2014) found no changes in uric

acid levels when tested at four points throughout the season with Portuguese soccer players. Another marker is the index provided by the Free Oxygen Radical Test (FORT) and Free Oxygen Radical Defence Test (FORD). Taking together the FORT and FORD tests (FFT) provide an index of oxidative stress that can now be tested at the point of care (Lewis et al., 2016). However, there is limited research into these markers in elite soccer and the invasive nature of blood sampling remains a limitation to regular monitoring.

2.3.3 Perceptual

Having been reported as a key measure by all recent surveys, subjective wellness assessments, in the form of self-report questionnaires (SRQs), appear to be the most prevalent fatigue measure used in high performance sport (McCall et al., 2015a; McCall et al., 2015b; Taylor et al., 2012). The simplicity of these measures allows them to be widely used and technological development is rapidly moving subjective assessments from paper-and-pen, to smartphones and web-based servers (Saw, Main, & Gastin, 2015b).

Subjective complaints, particularly of 'heavy legs', and changes in mood states have long been reported in cases of overtraining (Urhausen & Kindermann, 2002), although concerns have been held about the possibility for athletes to deliberately underreport fatigue in order to continue to train and compete (Urhausen & Kindermann, 2002). Despite these concerns, and the range of different subjective assessments being used, a recent review concluded that subjective measures are more closely related to fluctuations in training load than commonly used objective measures (Saw, Main, & Gastin, 2015a). In their systematic review (Saw, Main, & Gastin, 2015a), 55 original studies which involved concurrent use of subjective and objective wellness measures during regular training were analysed. The review found that subjective measures of wellbeing were reduced in response to acute and chronic increases in training load, and increased in response to acute reductions in training load. These findings were in agreement with the associations found between perceived measures of fatigue and muscle soreness and fluctuations in the daily training load among elite Australian Rules Football (AFL) players (Buchheit et al., 2013) and elite soccer players (Thorpe et al., 2015). Furthermore, the review found that there was generally no correlation between subjective and objective measures, with the authors stating this as a reason to include both types of measures in the monitoring process (Saw, Main, & Gastin, 2015a).

The review by Saw et al. (2015a) only included subjective wellbeing assessments that have been previously validated in the literature such as the Profile of Mood States (POMS; McNair, Lorr, & Droppleman, 1981) and the Recovery Stress Questionnaire for Athletes (RESTQ-A; Kellmann & Kallus, 2001). In the field however, shorter, custom-designed questionnaires are largely preferred (Taylor et al., 2012). Amongst practitioners, 80% using SRQs were opting for custom-designed SRQs so as to save time and to minimise the burden on the players (Taylor et al., 2012), which is understandable given that in return they can expect to receive greater player compliance (Saw, Main & Gastin, 2015b). The majority of teams surveyed by Taylor et al. (2012) were using SRQs daily. This is important because the more frequent the monitoring, the earlier signs of fatigue or overreaching can be detected (Saw, et al, 2015c). Extensive subjective assessments such as the POMS or RESTQ-A

are unlikely to be completed daily but shorter SRQs can be. There is also the potential for the more extensive assessments to be undertaken at certain stages of the season in order to supplement the daily SRQ (Saw et al., 2015a).

Interviews with athletes, coaches, and sports science and medical staff in high performance sport have revealed trends in how SRQs are being used in the field. In most cases subjective assessments are being completed electronically and automatically synced to databases accessible to relevant staff (Saw et al., 2015b, 2015c). Such systems provide three main benefits: convenience for the athletes; automatic databasing, which saves practitioners the time that would otherwise be taken to enter data themselves; and the possibility for automated alerts to be sent to coaching staff when a player is deemed at risk. SRQs in the field involve a four-stage process: collecting the data; reviewing the data; putting the data into context; and acting upon the data (Saw et al., 2015c). Once data is collected and reviewed in line with the athlete's historical norms, conversation with the athlete is often the first port of call when there are concerning data. Such targeted conversations allow clarification of issues a player is facing, which may otherwise not be brought to their attention. They also show players that their data is meaningful and acted upon by coaches and staff. Where necessary coaches and staff will use wellbeing data to manipulate training loads in order to prevent excessive fatigue and increased likelihood of injuries and illness, although the magnitude of change that determines such actions are often somewhat arbitrary (Saw et al., 2015c). Staff also cite improved inter-staff communication about player welfare and training loads as a benefit of regular wellbeing monitoring, as the data provide a common ground which can help to initiate conversation between disciplines (e.g. between coaching staff and sports science staff) (Saw et al., 2015b). Furthermore, player education and awareness of good recovery and lifestyle habits can be another benefit of these sorts of measures (Saw et al., 2015c). This being said, SRQs are still limited by the potential for players to answer out of habit instead of actual current wellbeing, or to deliberately over- or under-report fatigue in order to receive a reduced training load, or to ensure they are not rested for training or competition (Saw et al., 2015c; Taylor et al., 2012).

2.3.4 Performance

Theoretically, the most valid test for monitoring readiness to train (or compete) for a soccer player would be to have the player perform a full soccer match and assess their performance (Taylor et al., 2012). However, such direct and maximal performance testing is clearly counterproductive because of the extra fatigue it would impose, the risk of injury, and the time taken to perform the measurement (Buchheit, 2014). Furthermore, in the case of team sports such as soccer, there is no objective way to measure individual performance as there is with some individual sports (e.g. race times or throw/jump distances). One might examine the physical activity profile from a game, however, this is known to be influenced by a host of external variables such as tactical considerations and the standard of opposition, and does not represent a holistic analysis of match performance. Match performance clearly is not a feasible daily fatigue measure among soccer players however, various other short duration neuromuscular tests have been proposed as performance-based fatigue markers. Of high performance sports departments surveyed by Taylor et al. (2012) 61% reported the use of some form of performance test as part of their monitoring process.

2.3.4.1 Jump Tests

The most commonly used performance tests are jump tests (Taylor et al., 2012). Further analysis revealed that countermovement jump (CMJ) height was the predominant jump test used across the range of sports surveyed. CMJ is thought to be a good marker of neuromuscular fatigue because it incorporates the stretch-shortening cycle of the muscle (Gathercole, Stellingwerff, & Sporer, 2015; McLean, Petrucelli, & Coyle, 2012; Nedelec et al., 2012; Taylor et al., 2012). There are a number of methods used to assess CMJ, which differ in regards to their ease of use in field settings (e.g. training camps). The gold standard measure would be taken on a force platform but more transportable tools include contact mats, jump tree (e.g. Vertec), or, more recently, smartphone applications (Balsalobre-Fernandez, Glaister, & Lockett, 2015).

Despite its prevalence within high performance monitoring programmes, CMJ height has previously been reported to have a limited relationship with acute changes in training load in soccer players. Thorpe et al. (2015) found that among EPL players during a 17 day in-season period, CMJ height had a weak relationship ($r = 0.23$, $p=0.04$) with daily fluctuation in total high intensity running distance covered at training. No relationship between training load variables (total distance, high intensity distance, RPE) and CMJ height was found among elite youth players by Malone et al. (2015). Perhaps the tenuous relationship evident in these studies might be explained by the recent suggestions that analysing jump height alone may overlook changes that a more comprehensive jump assessment

would capture. Analysis of jump strategy/mechanics may better reflect acute fatigue status than traditional jump output measures (i.e. jump height) (Gathercole et al., 2015). When a range of alternative jump variables were compared for their ability to detect fatigue in elite snowboarders, the most responsive variables were peak force production and jump time (Gathercole et al., 2015). The authors suggested that fatigue may not necessarily reduce jump height, as athletes may be able to reach the same height, but by employing variations in their jump strategy or mechanics (Gathercole et al., 2015). Therefore, a more holistic assessment of jump performance may provide greater insight into fatigue development, than focusing on jump outcome alone.

The appeal of jump height analysis is due to the simplicity of the measure. However, the problem for those without force plates is how to make a holistic jump assessment using a simple tool. If more complex jump variables are able to be accurately measured using simple and inexpensive testing equipment such as contact mats, or even smart-phone applications (Balsalobre-Fernandez, Glaister, & Lockey, 2015), this would be a promising direction for athlete monitoring. However, there appears to be uncertainty about which metrics to measure and the magnitude of change which is meaningful (Taylor et al., 2015). Furthermore, the concerns raised by researchers working with elite soccer players about players' reluctance to perform maximal jumps following heavy training or match loads must also be noted (Thorpe et al., 2015). If practice is going to move away from measuring jump height perhaps an alternative would be to standardise jump height (e.g. players jump to a box of a set height, which they can reach submaximally) and assess alternative jump variables required to reach the height (e.g. under fatigue a player may require more time to generate the force required to jump onto the box, than they do when they are in a non-fatigued state).

2.3.4.2 Alternative Performance Measures

Other performance measures which provide an index of fatigue include single and repeated sprint protocols, intermittent running tests (e.g. Yo-Yo IR1 (Bangsbo, Iaia, & Krusturup, 2008)), and aerobic capacity tests. While the decrements in sprint and repeated sprint performance following match play and simulated soccer running tests have been well documented (Fatouros et al., 2010; Krusturup et al., 2006; Krusturup et al., 2010; Magalhaes et al., 2010; Mohr et al., 2004; Morcillo et al., 2015; Nedelec et al., 2012), there is no research into the daily fluctuations of these measures during regular soccer training and competition. This is likely to be because such maximal measures are considered inappropriate for daily testing in players who are already under heavy workloads. Therefore, performance measures such as these would seem more practical for assessing player fitness and adaptation to training programmes, at various stages in the season, as opposed to a daily measure of acute fatigue and readiness to train.

2.3.4.3 Correlating other Measures with Performance Measures

It is important that a fatigue measure is related to actual performance. For instance a measure that suggests a player is highly fatigued and not ready to perform, when in fact their performance is maintained or improved, is not a valid measure. The opposite is also true: if a measure reports that a player is in a non-fatigued state and ready to perform, yet their actual performance has dropped, then it is also a poor measure. Arguably, the most valid test for readiness to perform in soccer would be a performance test that closely replicates the physical demands of soccer (Taylor et al., 2012). However, daily testing is required in order to pre-empt the build-up of fatigue (Saw et al., 2015c), and an exhaustive performance test would be inappropriate to perform daily (Buchheit, 2014). Therefore, a logical solution might be to correlate less exhaustive fatigue tests with a selected performance test, such that performance might be predicted without carrying out the actual test. Although changes in some variables have been correlated with changes in chronic fitness levels (Boullosa et al., 2013; de Freitas et al., 2015; Flatt & Esco, 2016), to the best of the author's knowledge only one study has attempted to correlate fatigue measures with acute changes in performance (Buchheit et al., 2013) and no study has attempted to model the relationship between fatigue and performance such that predictions of performance could be made from fatigue data.

Buchheit et al. (2013) collected various fatigue measures daily during a 2-week preseason camp with professional Australian Rules Football players. During the camp performance was assessed using the Yo-Yo IR2 (collected pre, mid, and post-camp) and total running distance and high speed running ($>14.4 \text{ km}\cdot\text{h}^{-1}$) distance during standardised sport-specific drills on four occasions (days 2, 5, 9, 11). Yo-Yo IR2 performance improved over the training camp with this change largely correlated with changes in HR measures (HR_{ex} during submaximal exercise and HRV) and subjective wellness measures, but not correlated with changes in salivary cortisol concentration. Comparatively, with the exception of subjective wellness, there was no correlation between the fatigue measures and distance covered during standardised training drills (Buchheit et al. 2013).

Further study is required to examine the correlation between commonly used fatigue measures and daily soccer-specific physical performance. One decision for researchers will be which performance test to select. The work by Buchheit et al. (2013) suggests that distance covered during sport-specific drills may not be the answer, due to the technical and tactical considerations that also affect running during these drills. In this respect controlled tests such as the Yo-Yo IR2 might be better suited, however, such an exhaustive test is unlikely to be carried out every day. Shorter repeated sprint protocols may provide a less exhaustive solution as they have been shown to reflect match running output (Carling et al., 2012; Rampinini et al., 2007).

2.4. Summary

In summary, the general demands placed on soccer players during games have been well established, however, more recent research suggests that players are now covering more distance at high intensity and performing more explosive sprints. Soccer players also take part in several weekly training sessions. Total distance covered during an in-season week can range from 26-36 km.

Decisions about players' fatigue levels and readiness to perform must be made on a daily basis therefore regular fatigue monitoring is an essential part of elite soccer. National soccer teams face a unique set of challenges in that players will often arrive 4-5 days before a competitive fixture with accumulated fatigue from club environments, potentially further fatigued from long-haul international travel and in an unfamiliar climate. Therefore, the tests used to determine readiness to train must be simple to administer, non-exhaustive for the players, and must be able to be completed in a training camp environment (e.g. in a hotel) without access to laboratory equipment.

In order to research fatigue markers, it is often the case that soccer fatigue must be generated through some artificial means. The closer the fatiguing activity replicates typical soccer fatigue the more valid it will be. If the study design requires participants to complete the same absolute, or relative, workload (e.g. where two groups are being compared) a more controlled approach is needed and the LIST might be a good solution as it incorporates turning elements not replicated by treadmill tests. However, if the degree of fatigue does not need to be standardised, a soccer game or training session, provides a more ecologically valid solution as other game aspects such as ball striking, tackling, jumping, and backwards running are replicated.

In the field fatigue monitoring is widely used with the most commonly used measures being subjective wellness assessments in the form of self-report questionnaires. Validated subjective wellness assessments have been found to be more closely related to changes in training load, than commonly used objective measures, however, the majority of practitioners are using shorter, non-validated questionnaires in order to save time and minimise the burden on players. HR measures, particularly morning resting HRV, provides a good measure of early adaptations to training, however its usefulness as a daily marker of fatigue is limited by its high daily variation with researchers suggesting that weekly average and CV of HRV provide more reliable measures. Biochemical measures are not commonly used in the field and are often limited by their invasive nature, and by the cost and expertise involved in analysing samples. Salivary immunoglobulin-A provides a valid measure of the first line of immune defence and can be measured in the field (Morgans et al., 2015). Most performance measures cannot be performed daily because of the extra fatigue they impose, however power-based tests such as jump tests, in particular CMJ, are used commonly in the field.

Jump analysis is likely to move away from focusing on jump height and towards a more holistic jump assessment including analysis of velocity and force variables.

The principle of specificity suggests that the most valid test for readiness to perform in soccer would be a performance test that closely replicates the physical demands of soccer, however, such a test would be inappropriate to perform daily. Therefore, an interesting avenue of research remains to correlate simple fatigue measures with a relevant performance measure. Further work is needed in this area to identify which measures best correlate with performance, which performance measure best reflects readiness to perform in soccer, and how to create a model by which performance can be predicted from simple fatigue measures, without carrying out the performance test itself.

Chapter 3: Methods

3.1 Subjects

Fifteen male amateur soccer players from local clubs volunteered to participate in the study (age = 22.6 ± 2.5 years; height = 177.8 ± 4.6 cm; weight = 75.1 ± 7.5 kg; estimated $VO_{2max} = 50.4 \pm 3.7$ ml·kg⁻¹·min⁻¹). One participant had to withdraw from the study because of conflicting time requirements leaving a total of 14 participants. The experiment was completed after the end of the players' regular soccer season at their respective teams. All participants were fully informed about the aims, experimental protocol, and requirements of the study and gave written consent before the commencement of the study. The experiment was approved by the Massey University Human Ethics Committee.

3.2 Experimental design and procedures

The players completed a range of fatigue measures and one performance measure immediately before and after undergoing the Loughborough Intermittent Shuttle Test (LIST) protocol, and again 24, 48, and 72 hours post-LIST. For the week prior to the study participants were asked not to change their dietary habits or to undertake any strenuous exercise, or consume any alcohol, in the 72 hours before and after the LIST. Participants were allowed to continue their habitual caffeine intake but were asked not to consume any caffeine in the two hours prior to any of the testing sessions. The entire study was carried out over a two-week period following the end of the soccer season. All testing sessions were carried out in the evening (18:00-20:00) on the same artificial soccer surface in similar conditions (14-16°C; 63-80% rh).

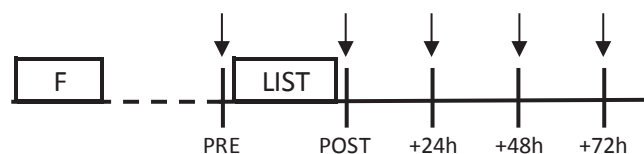


Figure 3.1 – Study timeline. Vertical arrows indicate when fatigue and performance tests were conducted. F = Familiarisation; LIST = Loughborough Intermittent Shuttle Test; PRE = immediately before LIST; POST = immediately after completion of LIST; +24h = 24 hours after completion of LIST; +48h = 48 hours after completion of LIST; +72h = 72 hours after completion of LIST.

On the day of the LIST players arrived at the testing venue and completed all the fatigue measures and the RSA test. The fatigue measures taken included perceptual wellbeing, functional soreness, and, countermovement jump (CMJ) height. As well as these measures participants also recorded HRV and RHR each morning. After completion of these measures all participants undertook the full LIST protocol. The same fatigue measures and performance measure were then completed

immediately post-LIST. For the next three days the players reported to the testing venue to complete the same set of fatigue and performance measures.

3.3 Preliminary measures

Exactly one week before the main trial players attended a familiarisation session at the same artificial turf. During this session players were familiarised with all the measures and anthropometric measures were taken. A Yo-Yo Intermittent Recovery Test Level 1 was completed to assess aerobic fitness of the group. The Yo-Yo IR1 test was performed as previously described (Bangsbo et al., 2008). Briefly, the test required players to perform 2 x 20-m shuttle runs at increasing speeds as indicated by an audio signal. Between each 2 shuttle runs there was a 10-second active recovery period during which players jogged around a marker placed 5-m behind the start marker. Players ran until they volitionally stopped running, or until they had failed to keep up with the audio signal two times. Scores were reported as the distance covered until the point they dropped out of the test.

3.4 The Loughborough Intermittent Shuttle Test

The LIST is a 90-minute running protocol designed to replicate game running in soccer. The test has been used extensively in the literature and has been previously described by Nicholas et al. (2000). In brief, the test involves 6 x 15-minute blocks of intermittent exercise interspersed by 3-minute rest periods. Each block involves running between two lines 20-m apart at various speeds as indicated by an audio recording. There are 11 cycles in each 15-minute block and each cycle involves the following shuttles in this order:

- 3 x 20 m walks ($1.5 \text{ m}\cdot\text{s}^{-1}$)
- 1 x 15 m maximal sprint
- 4 s recovery
- 3 x 20 m jogs ($55\% \text{ VO}_{2\text{max}}$)
- 3 x 20 m runs ($95\% \text{ VO}_{2\text{max}}$)

The level of the test was set at the average $\text{VO}_{2\text{max}}$ of the group. $\text{VO}_{2\text{max}}$ was estimated from the average distance covered during the Yo-Yo IR1 test according to the equation below developed by Bangsbo et al. (2008):

$$\text{VO}_{2\text{max}} (\text{ml}\cdot\text{min}^{-1}\text{kg}^{-1}) = \text{IR1 distance (m)} \times 0.0084 + 36.4$$

Heart rate (HR) was monitored throughout the LIST using chest straps (Team2, POLAR, Kempele, Finland). Ratings of perceived exertion (RPE) were recorded using the Borg CR10 scale (Borg, 1998)

during the final walk of each block. Participants drank water ad-libitum during the rest periods between blocks. Participants also wore 10 Hz (interpolated to 15 Hz using accelerometer data) GPS units in purpose-built bibs (GPSports, Canberra, Australia) in order to measure total distance covered, high intensity running distance (HIR > 5.5 m·s⁻¹), and sprinting distance (SPR > 6 m·s⁻¹). These speed zones are similar to those used in previous studies (Casamichana, Castellano, & Castagna, 2012; Malone et al., 2015).

3.5 Repeated Sprint Ability

RSA was chosen as the performance test because it has previously been correlated with match running variables (Carling et al., 2012; Rampinini et al., 2007). In order to minimise the accumulation of further fatigue on top of the LIST protocol a short 3 x 30-m sprint protocol was selected. The test was measured using timing gates (TC Timing System, Brower, UT: Draper, USA). Split times were taken after 5 and 10-m. Participants started each sprint with their front foot 0.5 m behind the first gate. There was an active recovery period of 25-seconds between sprints during which time participants returned to the starting mark for their next sprint. Participants were consistently encouraged to perform all sprints with maximal effort. Prior to completing the RSA test participants performed a standardised 10-minute warm up involving jogging, dynamic stretching, and four practice sprints of increasing intensity.

3.6 Countermovement Jump

Vertical jump performance was assessed by countermovement jump (CMJ) height using a timing mat (Probotics, JustJump, Alabama, USA). CMJ height was selected as the jump variable because of its simplicity to measure and the fact that it incorporates the stretch shortening cycle of the muscle. All jumps were performed with hands on hips to isolate leg power. As a standardised warm up participants performed 8 body weight squats and then 3 practice jumps of increasing intensity. The depth of the countermovement was self-selected by participants. Three attempts were performed and the best score was taken. CMJ attempts were separated by a 1-minute rest period.

3.7 Resting Heart Rate and Heart Rate Variability

Participants performed a 1-min measurement of HR immediately after waking every morning starting the morning after the familiarisation, finishing on the third morning following the LIST. Measurements were taken using the ithlete HRV mobile application and accompanying ithlete Finger Sensor (HRV Fit Ltd., Southampton, UK). The HR measurement was taken in a seated position with the finger sensor placed on the index finger of the left hand. During the 1-minute measurement participants followed the breathing cues displayed through the mobile app. The ithlete app provides

a measurement of rMSSD (log transformed and multiplied by 20 to provide a score on a 100-point scale). The application also recorded average HR during the measurement which was taken as RHR. Data was automatically synced into a password protected athlete Team account on a secure computer accessible only to the researchers.

3.8 Perceptual Wellbeing

Perceived wellbeing was assessed by the completion of a short Likert-scale questionnaire (Buchheit et al., 2013; McLean et al., 2010). A 9-point scale was used with standardised verbal anchors. The questionnaire contained five items pertaining to perceived fatigue, sleep quality, general muscle soreness, stress, and mood (See Appendix A). Participants completed the questionnaires individually and placed their completed sheet in a drop box.

3.9 Functional Soreness

A new protocol was devised for this study in order to provide a measure of functional soreness. Participants rated perceived soreness during a standard sit-and-reach test on a scale from 0 (no soreness) to 10 (worst soreness imaginable) (See Appendix B). Prior to completing the LIST participants performed the sit and reach test to the furthest point possible they could hold for three seconds without any soreness (i.e. a score of zero on the soreness scale). The point reached during the test was recorded and used as their baseline score; then at each subsequent sampling point (immediately post-LIST, +24, +48, +72) participants were required to reach this baseline mark. Participants were required to hold the stretch at the 'set point' for three seconds during which time they ranked their perceived soreness.

3.10 Statistical Analysis

Statistical analysis was performed using SPSS statistical software (version 20) and R (version 3.2.4). Mean and standard deviations were calculated for each measure. Data were checked for normality using the Shapiro-Wilk test. One-way analysis of variance (ANOVA) was performed for each measure to determine differences in the between-time points. Bonferroni post-hoc *t*-tests were subsequently performed to identify where the differences lay. The level of statistical significance was set at $p < 0.05$.

The correlation of each variable (change from baseline) with change in RSA performance (from baseline) was assessed using linear regression. Multiple regression analysis was also carried out with various models being created in an attempt to predict RSA performance. Subsequent analysis revealed that perceived fatigue (FTG) and general muscle soreness (GMS) variables were more appropriately used as binary data. Therefore they were transformed such that scores above or equal

to a certain value were counted as 1, and scores below that value were counted as 0. The cut off values were determined as 2.5 and 1.5 for FTG and GMS respectively. One General Model (GM) is presented for which no regard was paid to individuals. A further two individual models are presented: the Individual Intercept Model (IIM); and the Individual Slope Model (ISM). The following criteria were applied when interpreting the magnitude of correlations: <0.1 trivial; 0.1-0.3 small; 0.3-0.5 moderate; 0.5-0.7 large; 0.7-0.9 very large; 0.9-1.0 almost perfect (Hopkins, 2000).

Chapter 4: Results

Participants (n=14) covered 13 km during the 90 min LIST protocol at a mean RPE of 4.6 ± 1.8 au corresponding to 'somewhat heavy' to 'heavy' exercise. During the LIST the players performed an average of 1800 m HIR and 750 m SPR.

The table below displays the percentage change in each variable from baseline (i.e. following the LIST).

Table 4.1 – Percentage change of each measure from baseline. (LIST = Loughborough Intermittent Shuttle Test, 24h = 24 hours post-LIST, 48h = 48 hours post-LIST, 72h = 72 hours post-LIST, RSA = repeated sprint ability, CMJ = countermovement jump height, HRV = heart rate variability, FS = functional soreness, FTG = perceived fatigue, GMS = perceived general muscle soreness, au = arbitrary units) * indicates significant difference from baseline ($p < 0.05$).

Measure	Baseline	Immediately Post-LIST	24h	48h	72h
RSA	13.30 \pm 0.56 s	+ 5.1 \pm 4.5% *	+ 2.4 \pm 2.1% *	+ 1.2 \pm 2.0% *	+ 0.6 \pm 2.2%
CMJ	54.6 \pm 4.2 cm	- 4.5 \pm 4.6% *	- 3.6 \pm 4.6% *	- 0.42 \pm 6.4%	+ 0.9 \pm 5.7%
HRV	91.2 \pm 9.9 au	Not Taken	- 5.7 \pm 6.1% *	- 1.3 \pm 4.8%	+ 3.6 \pm 8.9%
FS (au)	0	+ 2.8 \pm 1.4 *	+ 3.6 \pm 1.5 *	+ 2.9 \pm 1.6 *	+ 1.7 \pm 1.7 *
FTG (au)	3.3 \pm 0.9	- 1.0 \pm 1.4 *	- 0.2 \pm 1.4	+ 0.0 \pm 1.2	+ 0.1 \pm 0.9
GMS (au)	3.2 \pm 0.9	- 1.4 \pm 1.3 *	- 1.3 \pm 1.0 *	- 1.1 \pm 1.0 *	+ 0.0 \pm 0.9

4.1 Repeated Sprint Ability

Immediately following the LIST RSA time (sum of 3x 30-m time) was increased ($p=0.001$; See Figure 4.1). RSA time remained increased at 24 hours post-LIST ($p=0.001$) and 48 hours post-LIST ($p<0.05$). After 72 hours RSA performance had returned to baseline ($p=0.372$).

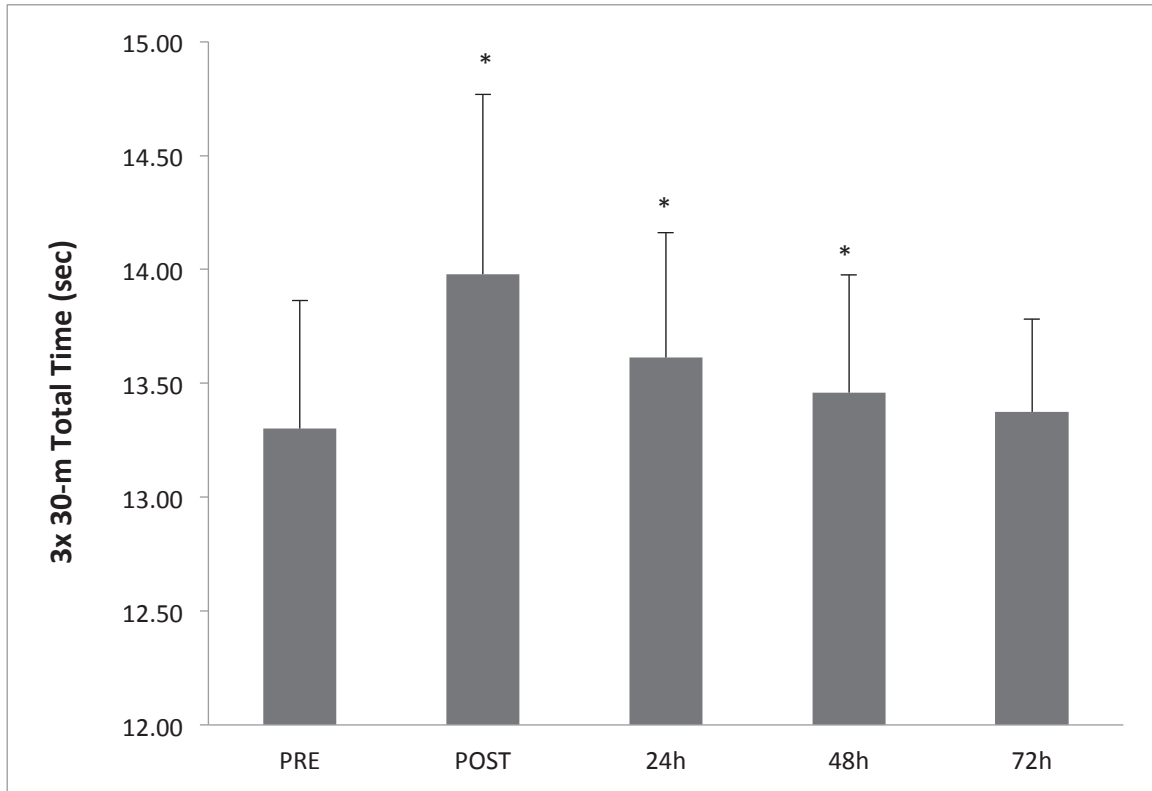


Figure 4.1 – Change in Repeated Sprint Ability (RSA) pre and post Loughborough Intermittent Shuttle Test (LIST) presented as mean \pm SD (n=14). (* indicates significant difference ($p<0.05$) from baseline, PRE = Immediately pre-LIST (i.e. baseline), POST = immediately post-LIST, 24h = 24 hours post-LIST, 48h = 48 hours post-LIST, 72h = 72 hours post-LIST)

4.2 Countermovement Jump

Immediately following the LIST CMJ height was reduced ($p=0.005$; See Figure 4.2). CMJ height remained reduced at 24 hours post-LIST ($p=0.013$) but had returned to baseline after 48 hours ($p=0.820$).

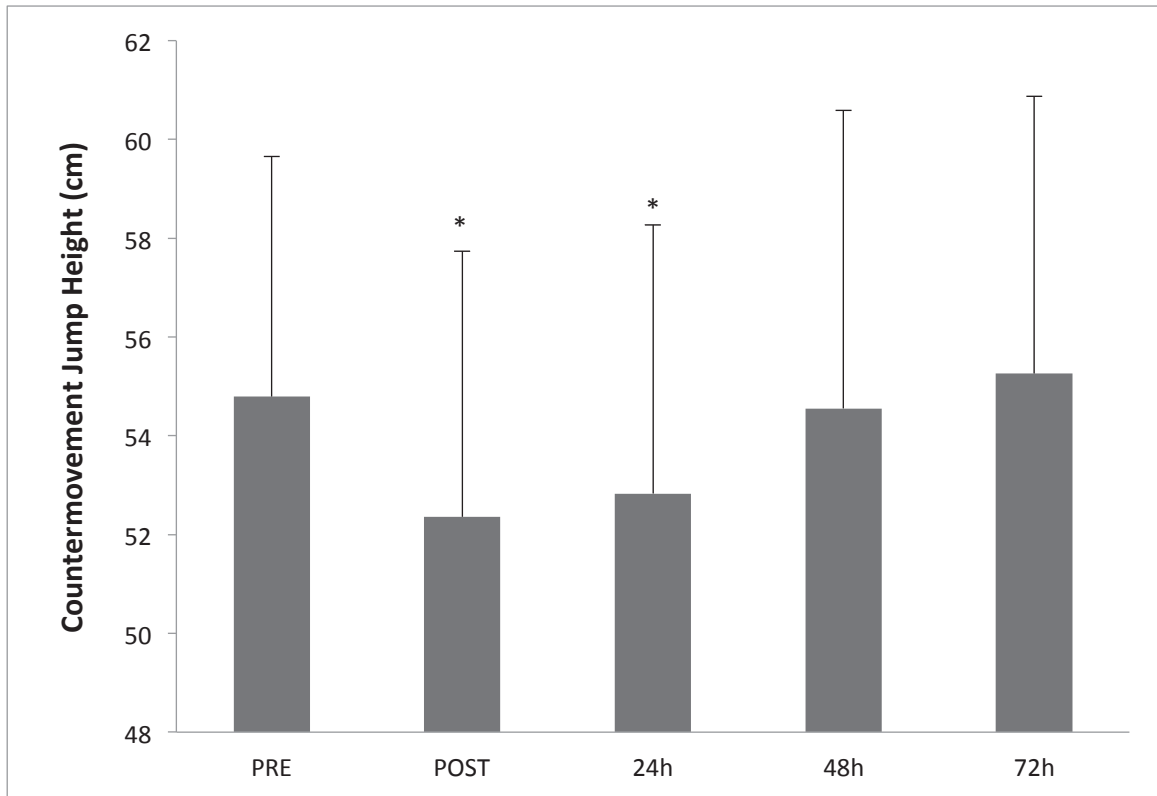


Figure 4.2 – Change in Counterovement Jump (CMJ) height pre and post Loughborough Intermittent Shuttle Test (LIST) presented as mean \pm SD ($n=14$). (* indicates significant difference ($p<0.05$) from baseline, PRE = Immediately pre-LIST (i.e. baseline), POST = immediately post-LIST, 24h = 24 hours post-LIST, 48h = 48 hours post-LIST, 72h = 72 hours post-LIST)

4.3 Heart Rate Variability

Three participants encountered technical issues with the ithlete Finger Sensor and mobile app so only 11 full data sets are included for this part of study. HRV was reduced 24 hours after the LIST ($p=0.017$). There was no difference between baseline HRV and HRV 48 hours post-LIST ($p=0.326$) and 72 hours post-LIST ($p=0.301$, See Figure 4.3).

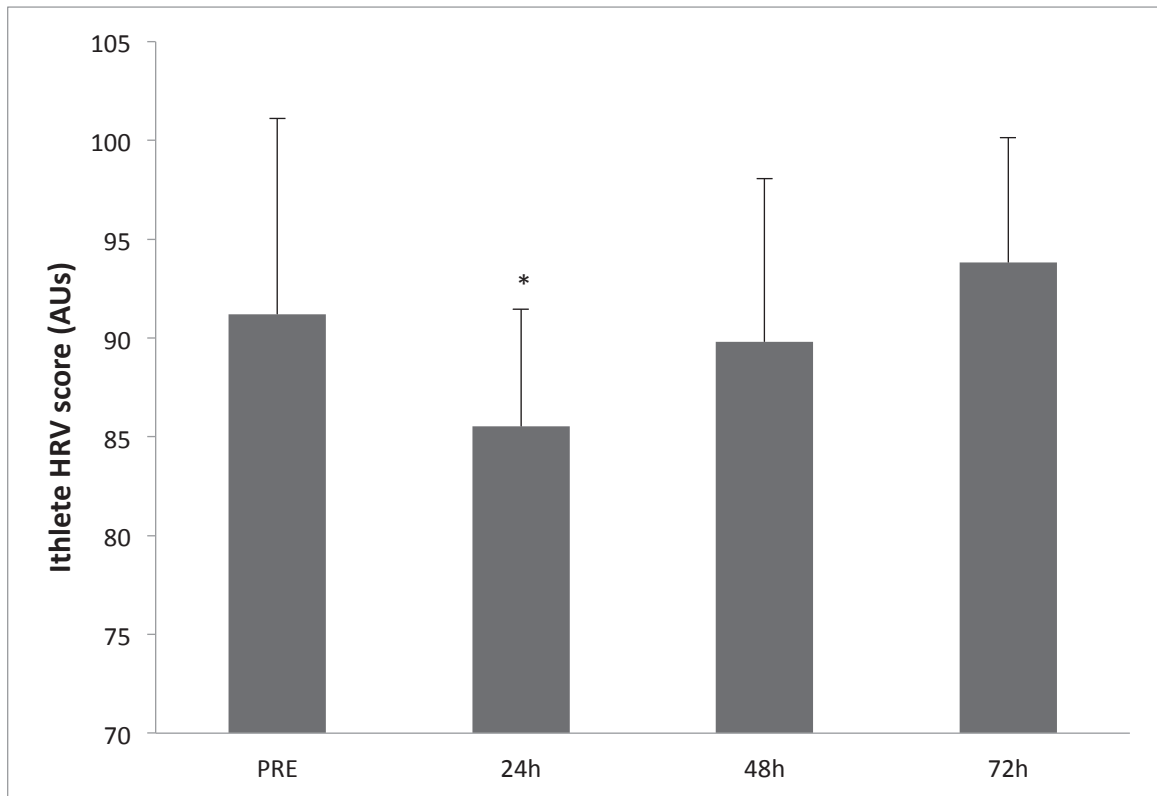


Figure 4.3 – Change in Heart Rate Variability (HRV) pre and post Loughborough Intermittent Shuttle Test (LIST) presented as mean \pm SD ($n=11$). (* indicates significant difference ($p<0.05$) from baseline, PRE = Immediately pre-LIST (i.e. baseline), 24h = 24 hours post-LIST, 48h = 48 hours post-LIST, 72h = 72 hours post-LIST)

4.4 Perceptual Wellbeing

Immediately following the LIST FTG ($p=0.024$) and GMS ($p=0.002$) were increased. FTG returned to baseline after 24 hours ($p=0.583$; see Figure 4.4a). GMS remained elevated at 24 ($p=0.001$) and 48 hours post-LIST ($p=0.002$) and returned to baseline after 72 hours ($p=0.789$; see Figure 4.4b). The other perceptual wellbeing markers (sleep quality, stress, and mood) remained unchanged throughout the study.

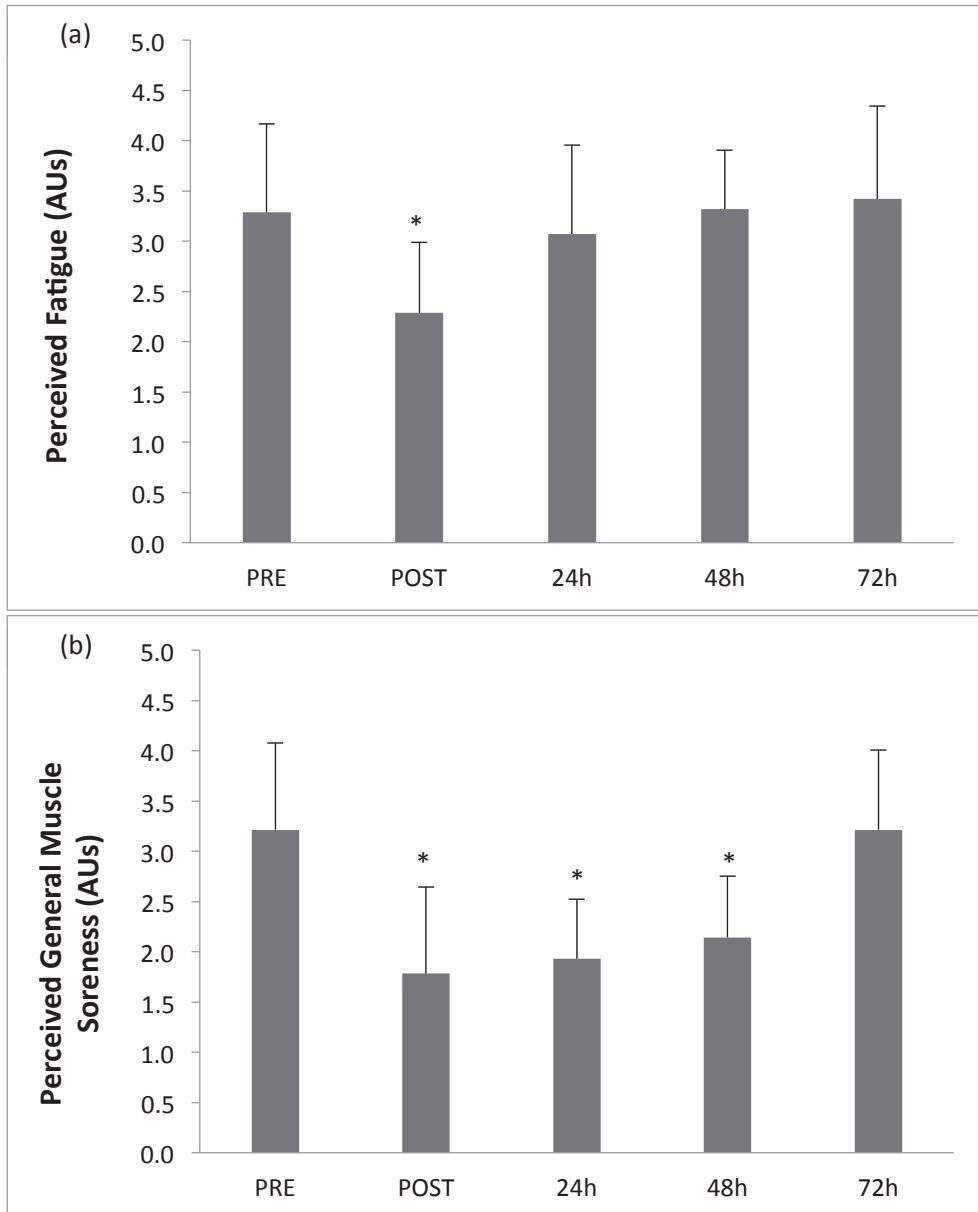


Figure 4.4 – Change in perceptual wellbeing (a – Fatigue; b – General Muscle Soreness) pre and post Loughborough Intermittent Shuttle Test (LIST) presented as mean \pm SD ($n=14$). (* indicates significant difference ($p < 0.05$) from baseline, PRE = Immediately pre-LIST (i.e. baseline), POST = immediately post-LIST, 24h = 24 hours post-LIST, 48h = 48 hours post-LIST, 72h = 72 hours post-LIST)

4.5 Functional Soreness

Immediately following the LIST functional soreness (FS) was increased ($p < 0.001$). FS remained elevated at 24 ($p < 0.001$) and 48 hours post-LIST ($p < 0.002$) and had not returned to baseline at 72 post-LIST ($p = 0.002$; see Figure 4.5).

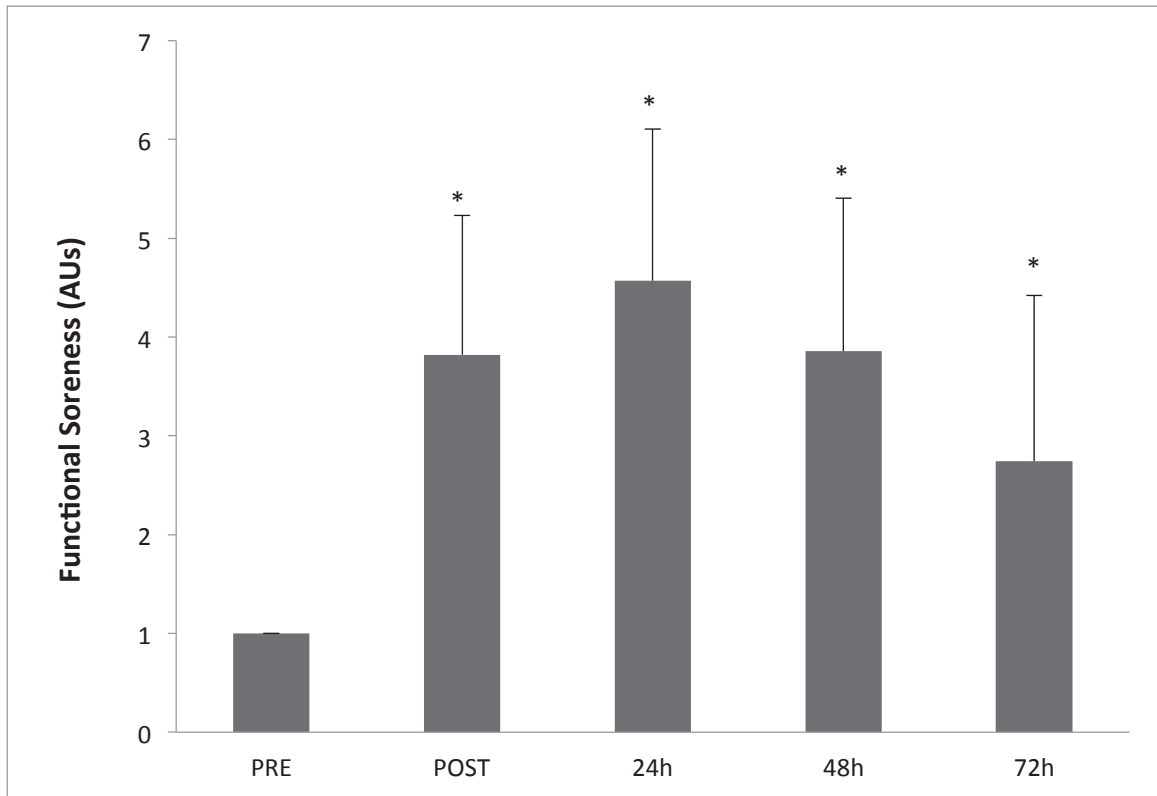


Figure 4.5 – Change in functional soreness (FS) pre and post Loughborough Intermittent Shuttle Test (LIST) presented as mean \pm SD (n=14). (* indicates significant difference ($p < 0.05$) from baseline, PRE = Immediately pre-LIST (i.e. baseline), POST = immediately post-LIST, 24h = 24 hours post-LIST, 48h = 48 hours post-LIST, 72h = 72 hours post-LIST)

4.6 Correlation of fatigue measures with RSA performance

The relationships between percentage change in each variable (from baseline) with percentage change (from baseline) in RSA performance are displayed in Table 2.

Table 4.2 – Strength of the relationship between percentage change in each measure (from baseline) and percentage change (from baseline) in RSA performance (RSA = repeated sprint ability performance, CMJ = countermovement jump height, HRV = heart rate variability, FS = functional soreness, FTG = perceived fatigue, GMS = perceived general muscle soreness) *HRV was plotted with reduced data points (n=44) because only 11 participants completed this aspect of the study and the measure was taken over only 4 time points (no data from immediately post-LIST).

Measure	r	Strength	p-value
CMJ	-0.402	Moderate	0.002
FS	-0.142	Small	0.298
FTG	-0.207	Small	0.125
GMS	0.023	Trivial	0.866
HRV*	-0.083	Small	0.644

4.7 Performance Models

The main variable used in the models was CMJ height since change in CMJ height had the strongest association with change in RSA performance. The y-intercept of the model was then adjusted using the binary FTG and GMS data (see statistical analysis section).

The individual models, which involved specific intercepts (and gradients for the individual slope model) for each individual player, were stronger than the general model (see Table 4.3).

Table 4.3 – Table displaying the strength of the three models.

Model	Adjusted r-squared	r	Strength
General Model	0.351	0.592	Large
Individual Intercept Model	0.729	0.854	Very Large
Individual Slope Model	0.812	0.901	Almost Perfect

General Model equation:

$$\text{RSA (Mean 30-m time)} = 5.664 + (-0.0190 \times \text{CMJ}) + (-0.0610 \times \text{FTG}) + (-0.0935 \times \text{GMS})$$

Intercept Model equation:

$$\text{RSA (Mean 30-m time)} = 5.462^* + (-0.0164 \times \text{CMJ}) + (-0.0748 \times \text{FTG}) + (-0.0890 \times \text{GMS})$$

Individual Slope Model equation:

$$\text{RSA (Mean 30-m time)} = 6.940^* + (-0.0446^* \times \text{CMJ}) + (-0.0748 \times \text{FTG}) + (-0.0890 \times \text{GMS})$$

(x = multiplied by, * = modified according to individual, CMJ = countermovement jump height in cm, FTG = binary perceived fatigue, GMS = binary perceived general muscle soreness)

Chapter 5: Discussion

The main aim of this study was to examine the relationship between various simple fatigue tests and daily changes in sprint performance (RSA). In order to do this fatigue was induced in 14 amateur soccer players using a 90 min intermittent exercise protocol (LIST). The main findings were that CMJ height was negatively correlated with RSA performance such that a reduction in CMJ height was associated with a greater total time in a 3 x 30-m RSA test. None of the other fatigue measures examined displayed a significant correlation with daily change in RSA performance. This study also aimed to produce a model by which readiness to perform could be predicted from simple fatigue measures. In this regard an individual model, where the intercept and gradient were adjusted for each individual, incorporating CMJ height and perceived fatigue and muscle soreness was found to be the strongest predictive model.

5.1 Recovery following the LIST

The LIST protocol was used to induce fatigue as it has been shown to replicate the running demands of soccer and result in similar recovery kinetics (Magalhaes et al., 2010). The total distance covered (13 km) as well as the distance covered during high intensity running (1800 m) and sprinting (750 m) during the LIST in our study was comparable to a competitive soccer match (Bangsbo, Norregaard, & Thorso, 1991; Mohr, Krusturup, & Bangsbo, 2003) and to those previously reported for completion of the LIST (Ali, Foskett, & Gant, 2014).

Immediately following the LIST RSA time increased by 5% (Table 4.1). This reduction of performance is greater than the previously reported decrement of 2-3% following friendly match play in males (Mohr et al. 2004; Krusturup et al. 2006), but similar to the 4% decline following a competitive match in female players (Krusturup et al., 2010). The greater performance drop in our study may reflect the differences between match play and simulated soccer running (i.e. LIST). Training status of the participants in our study may also have contributed to the greater decline in RSA performance however, participants in both the previously mentioned studies (Mohr et al. 2004; Krusturup et al. 2006) were not elite players and no assessment of aerobic capacity was reported for comparison. The aforementioned studies only examined RSA immediately post-match so comparisons with our data from 24-72 hours post cannot be made; however, the 72 hours taken for RSA performance to recover in our study is within the range reported (5-96 hours) for sprint performance to fully recover (Nedelec et al., 2012). CMJ height immediately post-LIST was reduced by 4.5% and had recovered by 48 hours post-LIST. Previously greater reductions in CMJ height of 12% following the LIST (Magalhaes et al., 2010), and of 10% following match play (Fatouros et al., 2010) have been reported. Fatouros et al. (2010) also found CMJ height to be recovered after 48 hours. HRV was significantly reduced the

morning after the LIST. Reduced HRV following an intense training bout indicates a fatigued state (Buchheit, 2014). Sustained declines in HRV may indicate overtraining but in this case, presumably as the training stimulus was an acute bout, HRV returned to baseline after 48 hours. Perceived muscle soreness has previously been reported to peak 24 hours post-LIST and to remain elevated for at least 48 hours (Bailey et al., 2007) as was the case in the present study. However, further comparisons of the change in subjective measures are difficult because few studies have reported subjective wellbeing data in the days following a match or a match simulation activity.

5.2 Correlation of fatigue measures with RSA performance

Change in CMJ height was found to have a moderate negative association ($r=-0.402$, $p=0.002$) with change in RSA. RSA has previously been associated with CMJ height (Morcillo et al., 2015), however, this is the first time the relationship between daily change in the two measures has been assessed. The findings of the current study are somewhat surprising given that CMJ height has previously been reported to have a small positive relationship (Thorpe et al., 2015), and no significant relationship (Malone et al., 2015), with the previous day's training load. Taken together these findings may indicate that CMJ height may better reflect daily readiness to perform than it does the previous day's workload. Of interest are recent suggestions that analysing jump height alone may overlook changes that a more comprehensive jump assessment would capture. Analysis of jump strategy/mechanics may better reflect acute fatigue status than traditional jump output measures (i.e. jump height) (Gathercole et al., 2015). However, such a jump assessment was beyond the scope of this study which focused on simple fatigue measures that could be used in field settings.

Perceived measures of fatigue and muscle soreness have previously been associated with fluctuations in the daily training load among elite Australian Rules Football (AFL) players (Buchheit et al., 2013) and elite soccer players (Thorpe et al., 2015) and have been suggested to better reflect changes in training load than commonly used objective measures (Saw et al., 2015). Buchheit et al. (2013) also found a large relationship between total wellness (sum of fatigue, sleep, muscle soreness, stress, and mood scores) and distance covered during Yo-Yo IR1 and AFL-specific drills. In the present study a small and negative association was found between change in perceived fatigue and RSA (Table 4.2). Although non-significant this relationship was in the general direction expected such that mean 30-m sprint time increased when players felt more fatigued ($r=-0.207$, $p=0.125$). No relationship was found between perceived muscle soreness and RSA ($r=0.023$, $p=0.866$). One reason for the limited association between wellness scores and performance in this study may have been the participants' limited familiarity with the subjective wellness assessment measure. A longer period of time may be required to familiarise players with subjective scales, for example a whole

preseason period was used to familiarise elite players with the Borg CR-10 RPE scale (Kelly et al., 2016).

Although the average trend for HRV following the LIST was expected, HRV was not associated with performance in this study. HRV has previously been associated with daily variation in training loads (Buchheit et al., 2013; Thorpe et al., 2015) and with acute (Buchheit et al., 2013) and chronic (Flatt & Esco, 2016) changes in fitness. Unfortunately the analysis of HRV was limited by a reduced data count. Three participants encountered technological difficulties with athlete application on their smart phones and, as HRV was taken as a resting measure each morning, HRV was not recorded immediately post-LIST with the other measures, thus leaving 44 data sets for this measure (11 participants x 4 time points) as opposed to 70 (14 participants x 5 time points) for the other measures. However, that the daily change in HRV was not well correlated with daily change in performance may not be so surprising, given the high day-to-day variation in the measure and the variety of factors which contribute to HRV (Buchheit, 2014). A growing body of research appears to suggest that longer term changes in HRV and its coefficient of variation are better indicators of positive or negative responses to training, as opposed to daily HRV taken in isolation (Flatt & Esco, 2016; Le Meur et al., 2013; Plews et al., 2013). As such HRV may be less useful in the context of this study where the aim was to identify acute method(s) of determining readiness to play.

Our functional soreness measure displayed a small non-significant relationship ($r=-0.142$, $p=0.298$) with change in RSA such that an increase in felt soreness was associated with a slower mean 30 m sprint time. Interestingly, the new functional soreness measure displayed a stronger individual relationship with RSA than GMS ($r = -0.142 > r = 0.023$ respectively). However, this may have been due to the fact that baseline scores for all participants for this measure was set at zero (i.e. no soreness) whereas for general muscle soreness participants selected their own baseline.

5.3 Modelling performance

Regularly taking maximal performance measures, such as RSA tests or Yo-Yo tests, which might reflect fatigue/fitness status and readiness to perform, with soccer players is impractical given the heavy training and competition loads that players face during the season. Such tests are also impractical in international soccer windows where players often arrive in a fatigued state (from club soccer and long haul international travel) and need to be fresh for two competitive matches in the space of 10 days. Moreover, the equipment and time required to perform these measures is not always available. Given these considerations we aimed to develop a model by which other simpler and less exhaustive fatigue measures could be used to predict RSA performance, thus negating the need for intense maximal performance testing in the periods of intense competition. To the best of

the author's knowledge this is the first attempt to model acute changes in performance in such a way. Through analysis of the results three models were developed which differed in their degree of individuality. All models used the same combination of three factors in order to predict RSA performance. The main variable used in the models was CMJ height since change in CMJ height had the strongest association with change in RSA performance. The y-intercept of the model was then adjusted using the binary FTG and GMS (see statistical analysis section) data such that if the binary value of these measures was 1, then a certain value was subtracted from the y-intercept. In real terms, if the player's perceived fatigue and soreness were not of concern then the predicted RSA performance was better. However, a value of 2 or less for FTG (and 1 or less for GMS) triggered the y-intercept of the model to be shifted upwards, and therefore the predicted RSA time was slower.

The aim of this study was to develop a general model that could be used to accurately predict RSA performance with any group of players. However, with the small sample size of this current study the general model developed is limited in its accuracy and thus application. The GM had a strong relationship with RSA performance and explained 32% of the variation. Of note was the increase in strength of the relationship when binary FTG and GMS were added as factors ($r=0.592$), compared to when change in CMJ height alone was correlated with change in RSA performance ($r=-0.402$).

As models were progressively individualised the strength of the relationship became stronger. The Individual Intercept Model had a very large association with RSA performance ($r=0.854$) explaining 73% of the variation in performance. The Individual Slope Model, which had individual intercepts and slopes for each participant, had an almost perfect association with RSA performance ($r=0.901$) explaining 82% of the variation in performance. For practitioners, more work is required to develop individual models, however, subsequent predictions made about performance are likely to be more accurate. In a highly homogenous group a general model may be sufficient, however, the heterogeneity in our study population, as displayed by the range in estimated VO_{2max} ($43 - 56 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), may have been one reason why the individual models were superior to the GM.

5.4 In the field – practicality of the measures and models

The fatigue measures used in this study were, in comparison to other measures (e.g. biochemical), simple and could be incorporated into daily elite (or semi-professional) domestic or international soccer environments. Even when looking at one type of measure (e.g. vertical jump) there are different measuring tools that can be used which differ in their practicality, portability, and cost. We attempted to take simple measures with simple tools, so that our findings might be applicable to a range of settings, in particular the international soccer setting on which there is limited literature on

player monitoring (McCall et al., 2015). With this in mind it is pertinent that logistical and practical aspects of each measure are briefly highlighted.

Subjective wellbeing assessments are clearly the most affordable and simple monitoring tool for use with team sport athletes (Saw et al., 2015a). A review of practices in elite team sport environments found that most practitioners elect to avoid traditional comprehensive and validated assessments such as the Profile of Mood States (POMS) or the Recovery Stress Questionnaire for Athletes (RESTQ-A), in favour of 'custom' subjective wellbeing assessments which involve far fewer questions (Taylor et al., 2012). Accordingly, the subjective assessment used in this study was a brief questionnaire with 5 items each answered on a 5-point scale (Buchheit et al. (2013). Such an assessment could be incorporated into any team-sport environment, domestic or international. Depending on budget constraints, recently developed monitoring software might provide an elegant solution to smooth the process of data collection and databasing (Saw et al., 2015b). Despite the simplicity of subjective wellness assessments, support and education from coaching staff on the importance of these measures is key to maintaining compliance (Saw et al., 2015b).

The appeal of jump height analysis has probably been in large part due to the simplicity of the measure. However, recently the suggestion has been that alternative jump variables may provide far greater insight into fatigue status than jump height alone (Gathercole et al., 2015). If more complex jump variables could be accurately measured using simple and inexpensive testing equipment such as contact mats, or even smart-phone applications (Balsalobre-Fernandez, Glaister, & Lockey, 2015), this would be a promising direction for athlete monitoring. However, the concerns raised by researchers working with elite soccer players about players' reluctance to perform maximal jumps following heavy training or match loads must also be noted (Thorpe et al., 2015).

In the present study HRV was analysed using smartphone technology, which makes use of a 55-second HR recording. The software processes R-R intervals and Ln rMSSD is calculated and multiplied by 20 to provide a figure on an easily interpretable 100-point scale. The use of this technology has previously been validated by Flatt & Esco (2013). To the best of the author's knowledge the current study is the first to report HRV measures taken using the athlete finger sensor. The sensor is non-invasive and arguably simpler to use for athletes than a traditional HR strap, although current incompatibility of the app and the finger sensor with some varieties of smartphones is concerning. However, at the rate that such technology is developing, it is likely that smartphone assessments of HRV will become increasingly popular as a means of HRV assessment among elite team sport athletes (Flatt & Esco, 2016).

Chapter 6: Limitations

It is acknowledged that the results of this study must be interpreted in light of its assumptions and limitations. The aim of this study was to correlate simple fatigue measures with readiness to perform physically in a soccer match or training. In the case of this study performance was assessed using a previously developed repeated sprint ability (RSA) protocol (Krustrup, Zebis, Jensen, & Mohr, 2010). An assumption here was that RSA performance (as measured by the 3 x 30-m sprint protocol) was a relevant indicator of readiness to perform physically in a soccer match or training. RSA was chosen because it has previously been correlated with match running variables (Carling et al., 2012; Rampinini et al., 2007). In order to minimise the accumulation of further fatigue on top of the LIST protocol a short RSA protocol (3 sprints) was selected.

The training status, and to a lesser extent the number of the participants may also have been a limitation. There was no access to a professional club or international squad with which to conduct this study. This being said the estimated VO_{2max} and CMJ height of participants in this study, were comparable with semi-professional (Cohen, Zhao, Okwera, Matthews, & Delestrat, 2015) and professional players (Thorpe et al., 2015) respectively. A key difficulty associated with using amateur players from a range of local clubs was that we were unable to extend the study over a longer period in order to collect more data. This would have been easier to undertake in a professional setting where all players report for training or recovery on most days of the week.

Another limitation was the fact that 3 of the 14 participants were unable to complete the HRV aspect of the study due to technical issues encountered when using the *ithlete* mobile application on their smartphone. This reduced the sample size of our study for this section and therefore statistical power. However, this study was reliant on participants using their own smartphones in conjunction with the *ithlete* application and it was beyond our budget to provide participants with the latest smartphone models, which may have had greater compatibility with the app.

The use of a soreness measure that has not been previously validated could be considered a limitation, however, according to McCall et al. (2015) many of the monitoring practices used in elite soccer clubs have not been validated by literature. It is therefore necessary for research, such as this study, to attempt to validate practices which are actually used in real world soccer settings.

Chapter 7: Future Directions

More research is needed in order to determine the fatigue measures that are best correlated with performance, and simple enough to be incorporated into the daily measures of elite domestic and international soccer teams. A growing body of research is beginning to shine light on the usefulness (or otherwise) of some measures, and on variations of traditional measures, which might provide more insight into fatigue status (e.g. alternative jump variables, or possibly the new functional soreness measure used in this study) (Buchheit et al., 2013; Flatt & Esco, 2016; Gathercole et al., 2015; Saw et al., 2015a; Thorpe et al., 2015).

Alongside the need to identify the best fatigue measures, there is a need to determine which performance measure to correlate against these fatigue measures. In this study we used a short RSA protocol. If the study design was such that testing was not conducted daily, it might provide opportunity to use more strenuous physical tests such as the Yo-Yo IR1 (Buchheit et al., 2013). Previous research has also correlated fatigue measures against distance covered during sport-specific drills (Buchheit et al., 2013), however, this may be difficult in soccer as a host of external factors will also influence distances covered during soccer drills. One possible soccer-specific physical test might be to complete one block of the LIST and assess mean 15-m sprint time over the block. In addition future research may explore the relationship between fatigue measures and soccer skill performance, which is obviously another key factor in readiness to perform for soccer. Performance in a test such as the Loughborough Soccer Passing Test (LSPT) could be correlated against fluctuations in fatigue measures in order to assess this relationship.

Further research is required in order to refine the predictive models produced by this study before they can be implemented within elite soccer settings. In order to build a more accurate predictive model data should be collected over a longer period with elite players.

Chapter 8: Conclusions

There is a need to identify sensitive markers of acute fatigue, which can be taken daily in elite soccer settings. The most valid test for readiness to perform in soccer would be a performance test that closely replicates the physical demands of soccer, however, such a test would be inappropriate to perform daily. Instead, several potential markers have been proposed but little has been done to correlate these markers against actual performance. Therefore the aim of this study was twofold: (1) to examine the correlation between a range of simple fatigue tests and physical performance; and (2) to develop a model by which readiness to perform could be predicted.

This study found that following the Loughborough Intermittent Shuttle Test (LIST) repeated sprint performance, countermovement jump height, and heart rate variability were reduced, while perceived soreness increased, and subjective wellness declined. Of the fatigue measures used, only countermovement jump height was found to be correlated with repeated sprint performance. This may suggest that CMJ height is still a valid neuromuscular marker of readiness to train that can be implemented fairly simply within soccer teams.

Three models for predicting performance were developed which differed in their degree of individuality. Individual models were found to have a greater strength than the general model. For practitioners, more work is required to develop individual models (particularly for international teams who may have to rely on data shared from players' clubs) however, subsequent predictions made about performance are likely to be more accurate. Future studies are needed to refine these models in order that they might be used in domestic and international soccer settings to make decisions about readiness to train and perform.

Chapter 9: References

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Appendices

Appendix A – Perceptual Wellbeing Questionnaire

Name: _____

Date: _____

	5	4	3	2	1
FATIGUE	Very Fresh	Fresh	Normal	More tired than normal	Always tired
SLEEP QUALITY	Very restful	Good	Difficulty falling asleep	Restless sleep	Insomnia
GENERAL MUSCLE SORENESS	Feeling great	Feeling good	Normal	Increase in soreness/tightness	Very sore
STRESS LEVELS	Very relaxed	Relaxed	Normal	Feeling stressed	Highly stressed
MOOD	Very positive mood	A generally good mood	Less interested in others &/or activities than usual	Snappiness at team-mates, family and colleagues	Highly annoyed/irritable/down

Circle the appropriate response for each of the 5 rows. You can circle between responses (eg 3½) if that better reflects how you feel.

Appendix B – Functional Soreness Scale

Soreness Scale

0	No Soreness
1	
2	Mild Soreness
3	
4	Moderate Soreness
5	
6	Severe Soreness
7	
8	Very Severe Soreness
9	
10	Worst Possible Soreness