IMPACT OF TRAINING AND COMPETITION LOAD ON NEUROMUSCULAR RECOVERY, HORMONAL RESPONSE AND MATCH PERFORMANCE IN ASSOCIATION FOOTBALL

by

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This thesis is submitted in partial fulfilment of the requirements for the award of

DOCTOR OF PHILOSOPHY

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ABSTRACT

In team sports, the competition season requires a balance between training and recovery. To assist in this process, both internal and external load are quantified. External load can be measured using Global Positioning Systems (GPS) and sensors such as accelerometers. Internal load is commonly identified through session rating of perceived exertion (sRPE), biochemical response in addition to changes in performance tests. However, little is known about the interaction between training load, the response to this load, and performance.

Study 1 determined the response of countermovement jump (CMJ) performance and salivary testosterone and cortisol to low, medium and high accelerometer derived PlayerLoad™ following football match play. Flight time:contraction time (FT:CT) was the most sensitive CMJ metric, with a dose-response reduction for 42h post-match. There were post-match increases in testosterone and cortisol irrespective of PlayerLoad™ level, and substantial variability which limits the usefulness of hormonal markers.

Study 2 assessed the impact of training and competition load throughout a professional football season on FT:CT, testosterone, cortisol and testosterone:cortisol and match performance. The largest effects of internal load on performance occurred in the 3- to 14-day pre-match window. An association between increased load and lower rating of performance was identified in defenders, whilst strikers and wide midfielder's performance rating was higher with higher load. Change in load did not substantially impact FT:CT or the hormonal response, and there was limited impact of these measures on performance.

Study 3 examined the use of a commonly used football training drill; small sided game (SSG), for measurement of neuromuscular fatigue (NMF). Whilst high weekly load increased accelerometer derived metrics during the SSG, these modifications did not appear to be fatigue related. Lower FT:CT compared to baseline, was related to reductions in accelerometer derived variables during the SSG. The reductions in FT:CT and accelerometer variables in the SSG were followed by the same modifications to match activity profile. Therefore, a standardised SSG game may be a useful tool for the assessment of NMF.

This thesis provides insights into the links between training and competition load, the response to that load, and the impact on performance in elite male football players. The results offer practitioners useful approaches to monitor athletes and maximise their performance. Finally, this thesis demonstrates the utility of an SSG for the assessment of NMF.

STUDENT DECLARATION

"I, Amber Ellise Rowell, declare that the PhD thesis entitled "Impact of Training and Competition Load on Neuromuscular Recovery, Hormonal Response and Match Performance in Association Football" is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work".

Signature

[redacted]

Date 09th March 2018

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With the thesis now complete, I can reflect on what has been one of the most challenging yet amazing journeys. The transformation and personal growth that I have experienced throughout this PhD has been something that I never imagined would happen. I have learnt so much, not only intellectually with the material covered in this thesis but also on a personal level. The doubt I had in myself and my ability to achieve this was a constant battle that I had to overcome. I am beyond proud that I persisted and preserved when the easy option would have been to quit, and now seeing this through to completion I am overwhelmed with joy.

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have all had personal challenges throughout. But we have seen it through to the end together as a team and from the bottom of my heart, thank you for sticking it out with me and showing me that I can actually do this. Dad and mum, the support of you two goes well beyond allowing me to stay at home, and the financial assistance you have given me which I am so appreciative of. You have actually equipped me with the knowledge and the skills to be capable of achieving this. You have instilled in me the values of determination, strength, courage and grit to not give in when it got tough, to keep going, keep pushing and whilst I wasn't sure that I actually would, you enforced that I could. I love you forever. Mum, you are the strongest woman I know, I idolise and aspire to be like you. Dad, you have strength and determination and the willingness to get things done which you have instilled in me and thank you for always making me laugh.

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"The only limit to the height of your achievement is the reach of your dreams and your willingness to work hard for them"

~ Michelle Obama.

LIST OF ABREVIATIONS

2D	Two Dimensional
ACWR	Acute:Chronic Workload Ratio
AFL	Australian Football League
ANS	Autonomic Nervous System
AU	Arbitrary Unit
CK	Creatine Kinase
CMD	Central Motor Drive
CMJ	Countermovement Jump
CV	Coefficient of Variation
EWMA	Exponentially Weighted Moving Average
FT:CT	Flight time:Contraction time ratio
GAS	General Adaptation Syndrome
GPS	Global Positioning System
GRF	Ground Reaction Force
HIR	High-Intensity Running
HIT	High-Intensity Training
HR	Heart Rate
HRR	Heart Rate Recovery
HRV	Heart Rate Variability
Hz	Hertz
km/hr	Kilometers per hour
LPM	Linear Position Measurement
LPT	Linear Position Transducer
$m.min^{-1}$	Meters per minute
$m.s^{-1}$	Meters per second

MVC	Maximal Voluntary Contraction
N	Newton
N/kg	Newton per kilogram
POMS	Profile of Mood State
$pg.mL^{-1}$	Picogram per deciliter
RF	Radio Frequency
RPE	Rating of Perceived Exertion
RHIE	Repeat High-Intensity Effort
s	Seconds
SD	Standard Deviation
SJ	Squat Jump
SSC	Stretch-Shortening Cycle
SSG	Small-Sided Game
T:C	Testosterone:Cortisol ratio
TE	Typical Error
TRIMP	Training Impulse
$\mu g.dL^{-1}$	Microgram per deciliter
U.L	Units per litre
W	Watts
W/kg	Watts per kilogram

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PUBLICATIONS AND CONFERENCES

The following publications in international peer reviewed scientific journals and conference presentations are a direct result of the current thesis.

Publications

Identification of Sensitive Measures of Recovery Following External Load from Football Match Play. **Rowell, Amber E.,** Aughey, Robert J., Hopkins, William G., Stewart, Andrew J., Cormack, Stuart J. Int J Sport Phys and Perf. 2017. 12(7): 969 – 976

Effects of training and competition load on neuromuscular recovery, testosterone, cortisol and match performance during a season of professional football. **Rowell Amber E.,** Aughey, Robert J., Hopkins, William G., Esmaeili, Ali., Lazarus, Brendan H and Cormack, Stuart J. Front. Physiol. 2018. 9(668): 1-11

A Standardised Small Sided Game Can Be Used to Monitor Neuromuscular Fatigue in A-League Football Players. **Rowell Amber E.,** Aughey, Robert J., Clubb, Jo. And Cormack, Stuart J. Front. Physiol. 2018. 9(1011): 1-13

Conference Presentations

The Time-Course of Neuromuscular Fatigue Following an A-League Football Match. **Rowell, Amber E.** Asia Pacific Football and Futsal Seminar 2014.

The impact of elite A-league football match play on countermovement-jump performance, salivary cortisol and salivary testosterone. **Rowell, Amber E.** 8th World Congress on Science and Football 2015.

The impact of A-League football match play on countermovement jump performance and salivary hormones. **Rowell, Amber E.** Research to Practice 2016.

Invited Presentations

The Australian Council for Health, Physical Education and Recreation (ACHPER) conference – 2014.

Seattle Sounders Football Club sports science seminar – 2017.

Arsenal Football Club football department information session – 2018.

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CHAPTER 1. INTRODUCTION

Improving a team sport athlete's performance involves the delicate balance between intensified load to facilitate adaptation and improve performance and appropriate recovery time to protect against the detrimental impact of prolonged fatigue. This task is complicated in team sport due to relatively limited opportunities for training, and frequent matches during the competitive season (Gamble, 2006).

Association football (football) is often referred to as the 'World Game', played by males and females worldwide, with the biggest competitions including the English Premier League, Seri A, Bundesliga, La Liga, Major League Soccer (MLS), and in Australia specifically is the A-League. Specifically to football, ` a large proportion of training occurs with the team as a collective based on tactical patterns of play, developing technical skills and decision making (Garganta, 2009). This team based approach may limit the opportunity to provide an individualised training dose. Further, there has been limited research actually investigating the difference in playing positions response to team based training load.

The foundation of the training process is the General Adaptation Syndrome (GAS) (Selye, 1950), which describes the impact of stress on the body. Intensified training stress results in both positive (fitness) and negative (fatigue) outcomes (Banister, 1991, Foster, 1998). Fitness, which is the result of repetitive training stress is the positive response and relatively slow to develop. Fatigue, in contrast, accumulates and dissipates relatively quickly (Smith, 2003). Fatigue, whilst considered the "negative" consequence of training stress, is necessary to drive physiological adaptation (Smith, 2003, Impellizzeri et al., 2004). However, when training stress is not balanced with sufficient recovery, maladaptation and a decline in performance can occur (Selye, 1950, Fry et al., 1991).

Whilst reserarch has been conducted within football competitions worldwide, very little is known about the specific interactions between training load and competition load, fatigue and performance in A-League football players.

An important aspect of planning and managing training and competition load is via the quantification of external load. This process has become relatively straightforward and common with the use of micro-technology devices, such as global positioning systems (GPS) (Aughey, 2011). However, a limitation of GPS derived metrics is that they only provide a representation of external load that can be calculated from velocity metrics (Boyd et al., 2011, Montgomery et al., 2010). In team sports like football, movements such as changes of direction that cannot be adequately quantified with GPS are common (Arrones et al., 2014, Barrett et al., 2016a, Carling et al., 2008). Furthermore, these movements may be mechanically and metabolically costly and as result, speed and distance metrics my underestimate the true external load (Boyd et al., 2011, Castillo et al., 2017). Therefore, the use of high-frequency accelerometers that detect movement performed in multiple planes (x:anterior-posterior, y:medio-lateral and z:vertical) may provide a more global quantification of external load (Boyd et al., 2011).

Although external load provides an indication of "what the athlete has done", a critical aspect of training load quantification is the assessment of internal load or "how the athlete has responded" (Vanrenterghem et al., 2017, Akubat et al., 2014). This can be achieved with the use of a rating of perceived exertion (RPE) that requires athletes to rate the intensity of the session they have just completed using the modified Borg CR-10 scale (Borg, 1985). Furthermore, session load (sRPE), calculated as RPE x session duration provides an overall indication of the internal load experienced by an athlete (Foster, 1998).

Whilst sRPE is a widely used measure of an athlete's response to training and competition, a number of objective variables have also been used to quantify this response and in particular, provide information on the time course of recovery following matches (Borresen and Lambert, 2008b). These include various biomarkers such as testosterone and cortisol (Cormack et al., 2008a, Elloumi et al., 2003, McLean et al., 2010) and variables from performance tests such as a countermovement jump (CMJ) (Cormack et al., 2008a, McLean et al., 2010, West et al., 2014, Gathercole et al., 2015b). Despite numerous investigations into the response of a wide range of variables to team sport training and competition (McLellan et al., 2011, Thorpe and Sunderland, 2012, Hoffman et al., 2005, Martínez et al., 2010, Malone et al., 2015, Cormack et al., 2008b), there is little information describing either the response of these variables relative to the training and competition dose or the impact on subsequent performance as a result of changes to these measures (Lazarus et al., 2017). It may be argued that without this information, the selection of relevant monitoring tools to be used in the manipulation of training load is somewhat problematic.

A further limitation of the various measures investigated for monitoring the response to football training and competition load is that data collection can require expensive specialist equipment, or the analysis of data can be time consuming. For example, although the use of measures from a CMJ are often employed as a surrogate to laboratory based assessment, the limitation of variables that can be assessed with relatively unsophisticated equipment (e.g. jump from a linear position transducer; LPT or jump mat) is that they may lack sensitivity (Crewther et al., 2011, Claudino et al., 2017). Conversely, variables from a CMJ that have been demonstrated as valid indicators of neuromuscular fatigue in team sport athletes can only be collected with the use of an expensive force-plate (Cormack et al., 2008c, Claudino et al., 2017). With budgeting requirements of professional teams may restrict additional costing for equipment, providing a potential barrier for professional clubs seeking to perform high level testing and analysis in the applied setting. Identifying practical alternatives with the use of pre-existing equipment is appealing. Furthermore, the collection of measures (e.g. CMJ) that might be useful in determining whether athletes have returned to baseline pre-match values in order to help in decision making regarding training participation, generally require the completion of a specific protocol which must be conducted in addition to regular on-field training. The need for additional testing may be a further limitation to the regular use of CMJ assessment, and again warrants alternative practical assessment measures. Whilst on-field assessment can be utilised to assess aspects such as autonomic nervous system (ANS) status via the use of standardised running protocols (Buchheit et al., 2010b, Buchheit et al., 2012, Buchheit et al., 2008), this approach still requires completion of extra training that provides no tactical or technical benefit. In situations where training time is limited, this may compromise time that can be spent on more specific training. However, as neuromuscular fatigue (NMF), represented by the ratio of flight time:contraction time (FT:CT) from a CMJ has been shown to result in a subsequent modification to movement strategy measured via accelerometry in team sport athletes (Cormack et al., 2013), it is possible that existing neuromuscular fatigue also modifies movement strategy in a standardised football drill such as a small sided game (SSG). If such a modification is evident in a SSG, there is potential for this to impact the movement strategy seen in a match played in close proximity to the SSG. This would allow a SSG to be used as regular tool for the assessment of neuromuscular fatigue.

Statement of the problem

In order to effectively balance training and competition stress with adequate recovery to maximise performance, both the internal and external load are regularly quantified. However, little is known about the dose-response relationship in elite football players. Furthermore, there is limited understanding about the interactions between training and competition load, measures of the response to this load and subsequent performance. Finally, current protocols to objectively assess the response to training and competition load may be limited by the requirement for the completion of specific protocols using expensive equipment.

CHAPTER 2. REVIEW OF LITERATURE

2.1 The training process

In team sports, the training process prepares athletes for match play via integrating game specific tactical and technical elements with cyclical load (periodization) (Coutts and Aoki, 2001, Smith, 2003, Garganta, 2009, Delaney et al., 2016b). Periodization has been a generalised term used to describe the process of load planning in preparation for competition. The implementation, application and management of periodized load has developed substantially based on different coach philosophies, interpretations and styles, as well as technological advances allowing for the feedback of response (Kiely, 2018). Load periodization involves the intricate exchange between repetitive bouts of stressful stimuli and appropriate recovery to drive adaptation (McKenzie and Newhouse, 2008). The periodization process has long been associated as being based on the General Adaptation Syndrome (GAS); a theoretical model describing the process of response to stress; Figure 2.1 (Buckner et al., 2017, Gamble, 2006, Selye, 1950, Selye, 1965, Selye, 1951, Carlson, 2010).

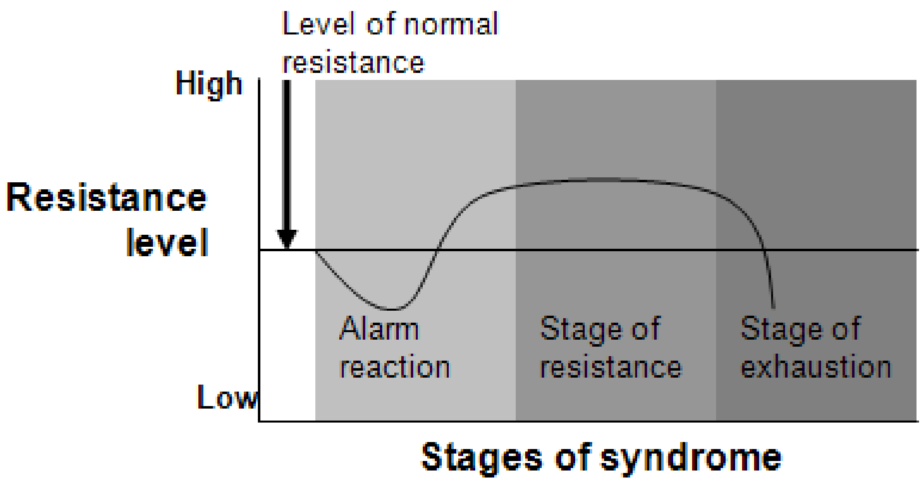

Figure 2.1 The three general adaptation stages. Reproduced from (Carlson, 2010).

The GAS summarises the response to stress in three key phases, starting with an initial "alarm reaction" (Selye, 1950, Selye, 1965). Alarm reaction describes the state of shock experienced by the body when first exposed to a new stressor (Selye, 1965). The reaction and impact on the body's systems varies in severity depending on the magnitude of the stress relative to athletes level of tolerance or "baseline" stress resilience (Gamble, 2006). After the "alarm reaction" the body enters "resistance", where adaptation to the stressor occurs in an attempt to restore homoeostasis (Selye, 1950, Selye, 1965). The resistance phase results in a increase in functional capacity to tolerate the level of stress via the process of supercompensation (Gamble, 2006, Kenttä and Hassmén, 1998). A stage of "exhaustion" occurs however if a stress response outweighs an individual's adaptive capability, or additional stress is incurred before the appropriate recovery from the first stressor (Selye, 1965). For performance to improve, athletes must be exposed to, and have the ability to withstand intensified load (Budgett, 1998). Intensified load results in a greater stress response, homeostatic disruption, biochemical stress on the physiological subsystems as well as potentially mechanical stress on the various tissues comprising the musculoskeletal system (Vanrenterghem et al., 2017, Selye, 1951, Selye, 1965). The impact of intensified load and the associated severity of disruptions causes an acute fatigue response and a decrement in performance (Halson and Jekendrup, 2004, Budgett, 1998). However, with appropriate recovery, the body becomes accustomed to tolerating an increased load, hence the resultant acute fatigue response is necessary to drive a positive adaptation and improve performance (Halson and Jekendrup, 2004, Budgett, 1998).

When athletes are not provided with adequate recovery, or when there is a sudden spike or drop in training volume or intensity, issues arise (Moxnes and Hausken, 2008). Prolonged intensified load can lead to underperformance (Budgett, 1998, Busso, 2003, Kenttä and Hassmén, 1998), whilst insufficient load can leave athletes underprepared for their match demands (Kenttä and Hassmén, 1998). Both over- and under-load can be intolerable for the athlete, increasing their susceptibility to injury or performance decrements (Polman and Houlahan, 2004, Bourdon et al., 2017). Individual athletes adapt to training and competition stress over varied time-courses, which is dependent on individual characteristics and recovery rate (Borresen and Lambert, 2008b). Within the team, there may therefore be an athlete experiencing overtraining, but the same stimulus might actually be insufficient for another athlete (Budgett, 1998). To overcome this, individualised training programs are suggested, however in a team sport environment this is extremely difficult to implement as the training dose is generally prescribed as a collective (Gallo et al., 2015). Therefore, understanding the time frame of training response and recovery is paramount within the monitoring program (Kenttä and Hassmén, 1998). The following sections will explore the interaction between fitness and fatigue along with specific models and assessment tools to help identify athletes' load response in more detail.

2.1.1 Differentiating between the two O's – Overreaching and Overtraining

Improving an athlete's performance requires exposure to intensified load to increase the athlete's capacity to tolerate higher training load (Polman and Houlahan, 2004, Kenttä and Hassmén, 1998). Exposure to intensified load occurs both acutely; from a single session during the training week, and chronically; over longer training blocks of weeks or months throughout the competitive season (Budgett, 1998, Fry et al., 1992). A period of intensified training is known as functional overload or overreaching (Halson and Jekendrup, 2004, Budgett, 1998, Fry et al., 1992, Kenttä and Hassmén, 1998). Overreaching increases an athlete's capacity and tolerance to increased load via positive stress adaptation (Polman and Houlahan, 2004, Halson and Jekendrup, 2004, Silva III, 1990). If a period of overreaching continues for an extended time without adequate recovery, this will cause an abnormal training response, and may develop in to a chronic fatigued state, referred to as overtraining, impacting an athlete's physical and mental state (Selye, 1950, Chiu and Barnes, 2003, Halson and Jekendrup, 2004, Fry et al., 1991, Fry et al., 1992, Kenttä and Hassmén, 1998). The response to periodized load is thus considered along a continuum from under-training and little adaptation or even maladaptation, to short-term functional overreaching through to overtraining and on the extreme right hand end of the spectrum, burnout; Figure 2.2 (Silva III, 1990, Stone et al., 1991, Halson and Jekendrup, 2004).

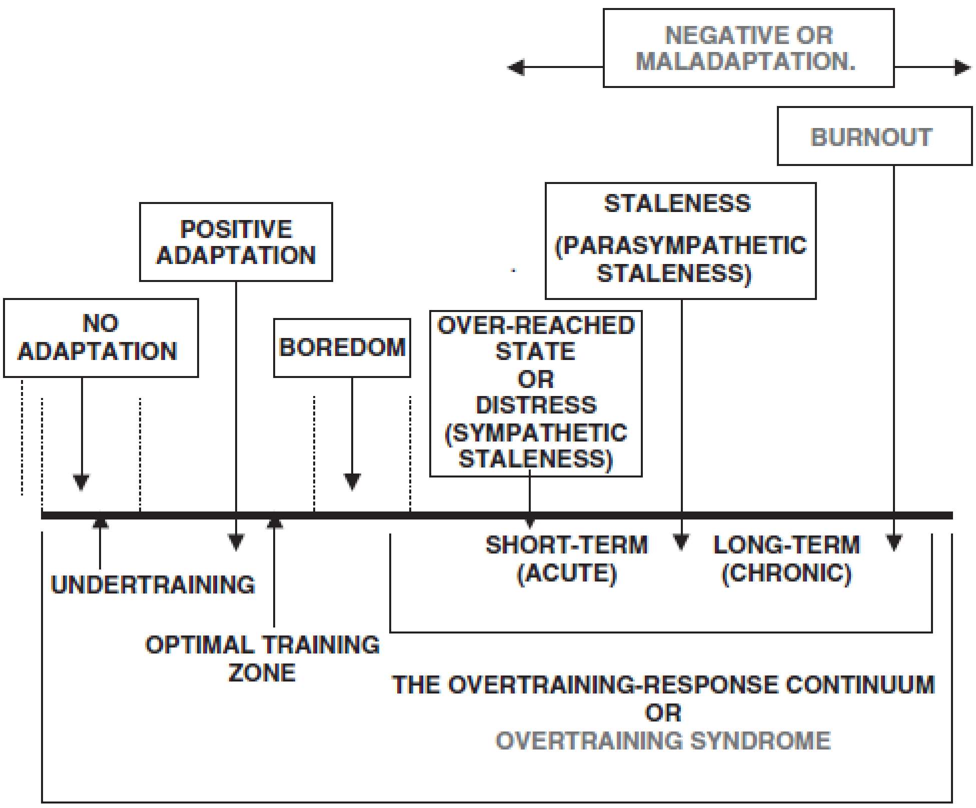

Figure 2.2 The training response continuum. Reproduced from (Polman and Houlahan, 2004).

In an attempt to predict an athlete's dose-response relationship to load during the training process, mathematical models have been developed (Busso et al., 1997, Banister et al., 1975a, Morton et al., 1990). Whilst performance is the outcome of multiple complex interconnected inputs (Figure 2.3), in general terms, performance is the result of the cross-over between positive and negative responses (Polman and Houlahan, 2004). To identify the interaction between fitness and fatigue responses, a number of differing predictive models will be explored, which have been applied across a variety of individual and team sports.

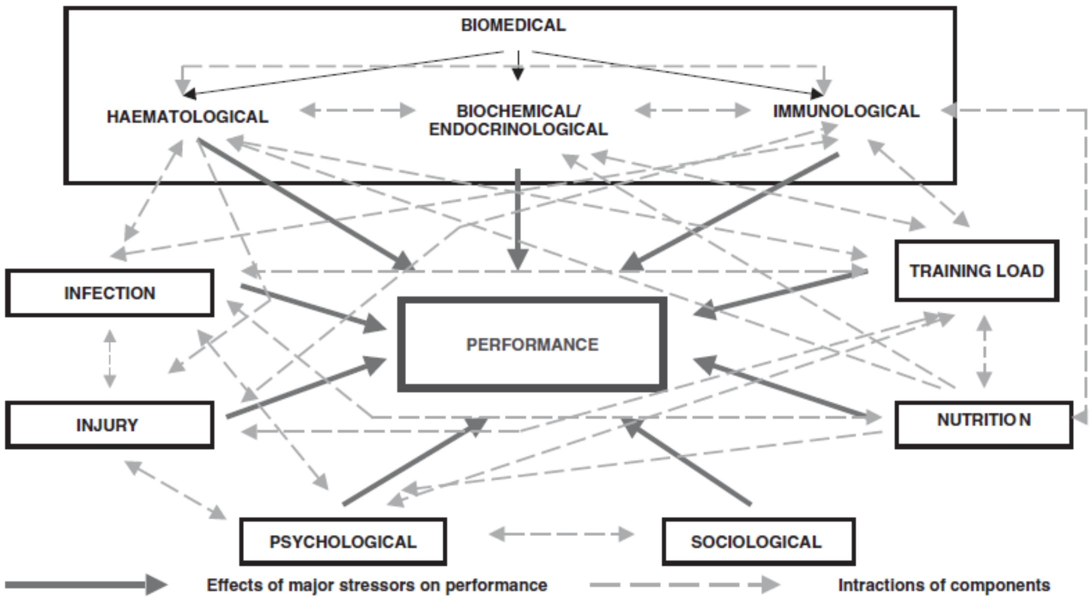

Figure 2.3 The interconnectedness of factors contributing to performance. Reproduced from (Polman and Houlahan, 2004).

2.1.2 Fitness-Fatigue model

Predictive performance modelling has developed from the premise that a prescribed exercise bout (dose) causes both disruptive negative (fatigue) and adaptive positive (fitness) responses (Busso, 2017, Banister et al., 1975a, Taha and Thomas, 2003, Banister et al., 1992). Performance is therefore considered a transfer function of the difference between fitness and fatigue (Calvert et al., 1976). The adaptive response of fitness is progressive in development, as the result of exposure to repetitive bouts of intensified load. In contrast, the disruptive response; fatigue which is experienced both acutely and chronically, generally dissipates quicker (Smith, 2003, Williams et al., 2016, Murray et al., 2016). The decaying nature of fitness and fatigue between exercise bouts is thus exponential, with fitness effects decaying at a slower rate than fatigue (Morton, 1997).

Predictive mathematical modelling, calculates the difference between fitness; the long lasting chronic adaptation to training and fatigue; the acute short term performance decrement (Calvert et al., 1976, Morton et al., 1990, Banister, 1991, Fitz-Clarke et al., 1991). Initial performance modelling by Banister and Calvert, utilised a simplistic prediction equation: $p(t) = k_1g(t) – k_2h(t)$, where performance at a given time; $p(t)$ was the function of fitness (k_1) minus fatigue (k_2) (Banister et al., 1975a, Calvert et al., 1976, Taha and Thomas, 2003, Bourdon et al., 2017). The fitness - fatigue model has been implemented to predict performance in a variety of individual, endurance based sports. This has included: running (Banister et al., 1986, Morton et al., 1990, Busso and Chatagnon, 2006), swimming (Avalos et al., 2003, Mujika et al., 1996a, Hohmann et al., 2000) and triathlon (Millet et al., 2002, Banister et al., 1999, Fukuba et al., 1999). To model exercise intensity, measures of heart rate (HR) response, blood lactate $[La^-]_b$, arbitrary training units (ATU) and training impulse (TRIMP) (Morton et al., 1990, Banister et al., 1975a, Taha and Thomas, 2003) have been used. The aforementioned indicators of intensity have been utilised with simplistic performance modelling in endurance sports, and display a linear relationship between work performed over time, as periodization of training is often modelled to a single competition (Issurin, 2009). Whilst this fitness-fatigue model conceptualised by Bannister has proved useful, the simplicity of a dose resulting in singular fitness and fatigue responses has been reviewed. Linear performance models are rigid in accounting for varying dose-response relationships between load and performance, and are limited to capturing the short-term temporary fatigue response, without providing insight into a cumulative chronic fatigue effect (Chiu and Barnes, 2003, Turner et al., 2017). Therefore, non-linear approaches for modelling performance may offer a better alternative for predicting performance, and these will be described in the following section.

2.1.3 Non-linear performance model

One of the biggest limitations of the fitness-fatigue model is the application of the model to a load cycle that involves smaller periodized cycles (across a week) and weekly competitions, such as that in team sports including football. Absolute load, intensity and total work performed across a week all induce their own fitness and fatigue responses (Chiu and Barnes, 2003), which highlights a restriction of the fitness-fatigue model with a single input variable reflecting total training strain (Busso and Thomas, 2006). In reality, and especially in team sports where athletes are exposed to recurring bouts of training stress, the result is multiple fitness and fatigue responses with varying time-courses of interaction. Within a team environment there is also the consideration that individual athletes respond and adapt differently to varying load exposure, requiring flexibility with modelling performance.

Initial modelling between training and performance by using the fitness-fatigue approach defined an antagonistic relationship, where increasing training input has a transfer to a rise in performance output (Hohmann et al., 2000, Banister and Calvert, 1980). Taking the concepts initially proposed by Banister's linear fitness-fatigue model, a progression was the development of a non-linear derivative model, where performance from a single training bout was considered an outcome of the intensity of previous cumulative load (Busso, 2003). Non-linear modelling allows for training and performance to follow an inverted-U-shaped relationship (Busso, 2003). The challenge for strength and conditioning and sport science practitioners is therefore to identify the "optimal" or "turning point" where training changes from driving positive performance responses over to a maladaptive response (Moxnes and Hausken, 2008). This relationship differs for each individual athlete, therefore individualised monitoring is favourable. To track an athlete's performance response to the training program, the use of nonlinear performance modelling approaches have been implemented across swimming, gymnastics and futsal to identify the interactions between training load and markers of fatigue (Hohmann et al., 2000, Sanchez et al., 2013, Milanez et al., 2014, Turner et al., 2017). With the foundation of understanding the interactions between fitness and fatigue responses to a training stress, further expansion of non-linear models to assess training load have been developed. Two of the most popularised and with particular focus on the application in team sports will be explored in further detail below.

2.1.4 Acute:Chronic ratio

To compare the interaction between fitness and fatigue responses, especially in sports with oscillating load, where training is periodized for weekly competitions, load performed over an acute period is compared to a rolling averaged chronic period. This is referred to as the acute:chronic workload ratio (ACWR) (Chiu and Barnes, 2003, Drew and Finch, 2016). The ACWR reflects the difference between fitness (chronic) and fatigue (acute) responses, to identify a spike in load that may lead to underperformance or injury/illness. A higher ACWR, reflects an increased fatigue state and is evident when acute load is higher than the chronic, whilst a lower ACWR occurs when chronic load is higher than the acute, and thus demonstrates more of a fitness effect (Murray et al., 2016). Published ACWR ranges include: ≤0.49; very low, 0.50 – 0.99; low, 1.0 – 1.49; moderate, 1.50 – 1.99; high and ≥2.0; very high (Murray et al., 2016).

The use of acute:chronic comparisons have been applied primarily to examine the relationship between training load and injury (Hulin et al., 2013, Hulin et al., 2015, Hulin et al., 2016, Malone et al., 2017b). The ACWR to identify injury risk was initially used with cricket fast bowlers. Data was collected from a total of 43 individual sessions, over a six year period from 28 fast bowlers (Hulin et al., 2013). When the weekly training-stress balance; calculated by one week acute external load (balls bowled per week in training and competition) compared to a four week rolling average load, exceeded 200% (≥ 2), reflective of a substantial spike in acute load, there was a threefold rise in injury risk in the following 1-week period. There was also a fourfold rise in injury risk when using internal load as the predictor (Hulin et al., 2013). However, the same study also identified that training-stress balances greater than 200% (internal load) and 100-149% (external load), provided a protection against injury risk in the current training week. This potentially highlights an adaptation and tolerance to increased load in professional athletes in the current training week but the consideration for the impact of a increased load on subsequent injury risk at a later time-point (Hulin et al., 2013). The study by Hulin et al. was limited to a case study on bowlers, with a relatively small number of individual sessions assessed. Further, only a single metric accounting for external load was explored, which requires further application of this approach in other sports to identify the link between load exposure on performance.

Expanding from the results in cricket bowlers to other team sport athletes, data was assessed across 2 seasons (pre-season and in-season phases) in elite rugby league players (Hulin et al., 2015). A very high ACWR (≥ 2.11), calculated by comparing total distance covered over a training week (acute load) to the 4 week rolling averaged distance (chronic load) had the greatest impact on injury risk in the current week and also the subsequent week (17% risk and 12% greater risk subsequently) (Hulin et al., 2015). An ACWR >1.5 was associated with a substantially increased risk of subsequent injury in rugby athletes (Hulin et al., 2015, Hulin et al., 2016). But more specifically in elite youth footballers (n = 32), data assessed across two consecutive seasons identified that when the ACWR (1-week load: 4-week rolling average acute load) of total distance and accelerations performed was >1.7 there was a heightened contact injury risk. Whilst in elite football players (n = 48), when the internal load determined via session RPE (sRPE) (Foster, 1998) was assessed throughout a competitive season, an internal load ACWR range of >1.00 to <1.25 acted as a protection against injury (Malone et al., 2017b). It was also identified in the same study with elite footballers that a high weekly cumulative load (>2120 AU - <3000 AU), or a substantial change in weekly load units of between 550 – 1000 AU were the biggest risk factors for injury (Malone et al., 2017b). Comparisons between cumulative load across 1, 2, 3 and 4-week periods and A:C from training sessions and match play, identified that the biggest contributor to non-contact injury was the amount of accelerations performed over the 3 week period (Bowen et al., 2016).

In the studies mentioned above, the biggest criticism has been that data has been presented on a group level and therefore, there is no sense of scope of the differentiation in load response between individuals within the team, or relative to positional groups. Furthermore, a global limitation of a rolling average to calculate ACWR is that the comparison of a 1 week to an average of 4 condenses the fitness and fatigue responses and the impact of smaller windows of load in comparison to a chronic exposure on recovery, and subsequent performance. The rolling average ACWR approach assigns the same relevance and weighting to a session performed during the acute period, and closer to the performance or injury, as a session performed in the chronic window (which could be up to 28 days prior). Given that the acute workload also constitutes a substantial part of the chronic workload with this traditional ACWR calculation, a mathematical coupling is evident and implies a spurious correlation (Lolli et al., 2017).

This in turn also leads to artifactually reducing the between-athlete variability in chronic workload (Lolli et al., 2017).Furthermore, a rolling average ACWR approach lacks the ability to account for phases of the season where functional de-loading; a deliberate reduction in training volume, due to variables including travel, congested match scheduling or quality of opposition (Kelly and Coutts, 2007). Similarly, the ACWR is not sensitive to a period of functional overreaching, where load is deliberately intensified. The impact of this deliberate manipulation of load may lead to an artificially lower or higher acute load relative to the chronic, which can artificially impact results and usage of this metric for load quantification. When reviewing the original fitness-fatigue concept proposed by Banister, it was well established that fitness and fatigue display a decaying nature over time, with a differing pattern of response with the introduction of each exercise stress bout. Therefore, a session performed 3 - 4 weeks prior would not have the same impact on the body as a session performed 1 day earlier to a performance or injury. The exploration of accumulated load over various windows may be more appropriate for team sports, such as football, given the periodization and manipulation of weekly load. Assessing the impact of different windows of acute and chronic load accumulation on performance, and accounting for the decaying nature of fitness and fatigue is an attractive concept requiring investigation.

2.1.5 Exponentially weighted moving average

An alternative method to the rolling average, used to compare acute to chronic load, is via an exponentially weighted moving average (EWMA), which accounts for the decaying nature of historical data (Hunter, 1986, Murray et al., 2016, Williams et al., 2016). The EWMA smoothes time series data by assigning a progressively lower weighting factor; lambda (λ_a) to data points further away in time, thus giving more impact to more recent data points. The EWMA equation is: $EWMA_{today} = Load_{today} \ x \ \lambda_a$

$+ ((1- \lambda_a) \times EWMA_{yesterday})$ (Williams et al., 2017, Williams et al., 2016). The λ_a represents the weighting factor (a value between 0 and 1), calculated by: 2/(N+1) where N is the number of days in the included period (Hunter, 1986). For example, the λ_a calculated for a 28 day average is 0.07 (2 / (28+1)), and the λ_a for data averaged over 3 days is: 0.5 (2 / (3+1)). The EWMA approach appears more appropriate for use, particularly for team sport training load, where the decaying nature of fitness and fatigue, and training adaptation within the model are appropriately reflected (Williams et al., 2016, Menaspà, 2016). Whilst a geometrical moving average, such as the EWMA is by no means a new model, stemming back to the late 1950s (Roberts, 1959) it has only recently been utilised for recalculating external and internal load measures for injury prediction, sleep efficiency and match performance in team sport athletes (Carey et al., 2017, Rossi et al., 2017b, Rossi et al., 2017a, Thornton et al., 2017, Lazarus et al., 2017). Across a 3-year period, a number of multivariate models were developed over 2 seasons to predict injury occurrence in the third season in Australian rules footballers (n = 75). Using the data from the first two seasons, training load variables including total distance, moderate running speed distance (5.0 – 6.7 $m.s^{-1}$), high-speed running distance (> 6.7 $m.s^{-1}$), PlayerLoad™ and internal load (RPE-based) were used to predict future injuries that occurred in the third season (Carey et al., 2017). Whilst the overall effectiveness of multivariate modelling to identify a substantial relationship between training load and injury in the study was limited, the EWMA provided a seemingly effective approach for re-calculating the relative metrics of load exposure across different 3, 6 and 21-day periods. However, the study by Carey, Ong et al. focused on the overall effectiveness of the multivariate modelling technique, failing to identify any specific interaction between load accumulation across the differing windows (3 day, 6 day and 21 days) on injury association. Further application of the

EWMA was performed with professional Italian footballers (n = 26), to account for the impact of GPS and accelerometer metrics from the 6 most recent sessions prior injury occurrence, to identify the measure/s more useful for predicting injury (Rossi et al., 2017b). It was observed that the biggest contributors to 42% of detected injuries was high metabolic load (distance covered with a metabolic power above 25.5 $W.Kg^{-1}$), and hard decelerating (above 2 $m.s^{-1}$), in the EWMA of the 6 most recent training sessions, prior to the injury (Rossi et al., 2017b). Metabolic load and decelerating was determined from 10 Hz GPS with in-built 100 Hz accelerometers. Similarly, the differing windows of load exposure were not explored.

A further application of the EWMA, in Rugby League athletes (n = 14), identified that during the 16 week pre-season an EWMA approach identified the impact of total distance, high-speed running distance (>4.0 $m.s^{-1}$), total accelerations/decelerations, and internal load (RPE-load) on sleep efficiency (Thornton et al., 2017). The windows of exposure were limited to 3 and 7 day recalculated EWMA periods. It was identified that increased total accelerations/decelerations had the greatest positive influence on sleep, demonstrating that athletes attempt to increase their quality of sleep on the back of intensified loading over 3 day and 7 day EWMA time-frames (Thornton et al., 2017). The importance of 3 and 7 day windows reflects the importance of acute load on athletes' sleep, which would have a subsequent impact to their recovery.

Whilst the above examples have highlighted the potential benefit and application of the EWMA, much more exploration is required, particularly relating to performance, as this is the ultimate goal of the training process.

The interaction between EWMA training load and match performance has recently been identified in AFL players. The assessment of different weekly summations (1.5, 2, 3 and 4 weeks) of a global load (combined external and internal metrics) measure on match performance according to playing positions was investigated (Lazarus et al., 2017). The study revealed that increased load (by 1SD) across differing EWMA weekly periods relative to playing positions resulted in a decrement in performance. Improved performance occurred at or around 1SD below the mean (Lazarus et al., 2017). The study with Australian footballers was limited in reporting weekly accumulated load, with the smallest window of 1.5 weeks, hence it is unknown if an acute load interacts with subsequent performance. Further, whilst combining external and internal load measures provides some insight into the global training response, further work is required to identify if the contribution of external load or internal response has a greater impact on performance. Overall, the approach of identifying different windows of load accumulation (acute and chronic) using the EWMA on performance is unknown in elite football, but an attractive concept warranting exploration.

2.2 Quantifying the response to training and match load

The training process requires effectively planned, monitored and manipulated load to promote adaptation and improve fitness whilst minimizing fatigue and the risk of non-functional overreaching (Coutts et al., 2017, Bourdon et al., 2017, Cummins et al., 2013, Scott et al., 2016b, Borresen and Lambert, 2009). In order to quantify fitness and fatigue, this involves the interconnectedness between what athletes do, and how they respond (Impellizzeri et al., 2005). Focusing firstly on “what athletes do”, the physical work performed and prescribed is referred to as external load. External load encompasses activity profile metrics of distance, speed, changes in direction, acceleration / decelerations and global body load experienced through ground and external contact forces (Halson, 2014, Aughey, 2011, Bartlett et al., 2017, Akubat et al., 2014, Cormack et al., 2014). External load accumulated during football match play can vary substantially, for players from match to match and between different playing positions, as it is contextualised by factors such as tactical formation, playing position, match location, climate and quality of opposition (Akubat et al., 2014, Di Salvo et al., 2007, Taylor et al., 2008, Garganta, 2009). Thus, overall football match movement produced by athletes is varied, based on their special positioning, the football specific actions performed and interactions with other players around the pitch (Rein and Memmert, 2016, Garganta, 2009). Acknowledging the variable nature of match external load and quantifying the activity provides a benchmark range for load manipulation (Buchheit et al., 2014). Utilizing this range can assist with ensuring athletes are exposed to peak match intensities and provided sufficient recovery to minimize fatigue leading in to the subsequent match (Leser et al., 2011, Delaney et al., 2016b, Delaney et al., 2017, Castellano et al., 2014, Scott et al., 2016b).

2.2.1 Quantification and monitoring of external load in football

Advancements in technology have simplified the process of tracking metrics to reflect players' external load, as well as providing feedback on player positioning, useful for tactical analysis (Leser et al., 2011). External load derivatives are determined from the change in athletes location over a given time (Liu et al., 2007). A number of differing systems are offered in the sporting realm for determining external load metrics, ranging from the more simplistic velocity based distance and speed, to more complex accelerometer derived changes in individual movement vectors. Technological advancements have allowed for the assessment of football player work rates during competition to progress substantially from single player tracking using video-based motion analysis (Reilly and Thomas, 1976), to multi-camera video-based monitoring systems, Local Position Measurement (LPM), and Global Positioning System (GPS) technology (Castellano et al., 2014, Buchheit et al., 2014, Leser et al., 2011, Frencken et al., 2010, Sweeting et al., 2014, Aughey, 2011, Varley et al., 2014, Hedley et al., 2010) which will be explored below.

2.2.2 Optical athlete tracking

Optical athlete tracking systems are commonly utilised within European football leagues. Video systems have the ability to track multiple players, the referee and ball with two-dimensional (2D) movement (Castellano et al., 2014, Di Salvo et al., 2006). The typical error (% CV) of an optical system when detecting velocity during paced 60 m runs, curved running over 50 m, maximal 15 m sprint and 20 m sprint with a left or right turn, compared to timing gates was < 2% (Di Salvo et al., 2006). However, the validation of the tracking system in the mentioned study by Di Salvo, Collins et al. displayed substantial limitations of comparing velocity detected by timing gates, movements being performed from a static start and to pre-determined target velocities. Further, the study involved recreational athletes; therefore, drawing the conclusion that movement analysis of professional footballers during match play using this technology was dubious. Optical tracking systems are expensive, requiring a permanent camera set up. Their biggest limitation though, is being only able to detect 2D change in athletes' position over time, and thus providing only velocity based metrics associated with distance and speed. Given the complex, multi-plane movements contributing to overall football activity, limiting only the 2D contribution underestimates total movement as vertical movement is excluded (Barris and Button, 2008, Castellano et al., 2014).

2.2.3 Local Position Measurement (LPM) System

Overcoming the limitations posed by the optical tracking systems has been the integration of detecting player movement with sensors worn by each athlete. Local Position Measurement (LPM) (Frencken et al., 2010, Buchheit et al., 2014) and Global

Positioning System (GPS) (Aughey, 2011) technology provides a scope to quantify external load outdoors as well as indoors, with every player accounted for.

The LPM technology requires a transponder worn by athletes in a custom elastic harness, which sends signals to a number of antennas (base stations) and transponders positioned around the edge of the pitch or court for indoor sports (Hedley et al., 2010). The LPM systems utilised in team sport for both outdoor and indoor tracking include radio frequency (RF) (Frencken et al., 2010, Leser et al., 2011), Wireless Ad-hoc System for Positioning (WASP) (Hedley et al., 2010, Sweeting et al., 2014) and Ultra-Wideband (UWB) (Serpiello et al., 2017) systems. The LPM systems are based off the detection of a time of arrival (TOA) of the transponders worn by athletes relative to the anchor nodes positioned in known locations around the side of the pitch / court / stadium (Hedley et al., 2010). A periodic beacon is transmitted between each node, to identify the TOA from one location to the next, relative to the node position.

Whilst the overall LPM systems display a high sample frequency (for example the RF samples at 1000 Hz), this is then distributed between the active transponders. For example an RF system tracking a football game can provide data at a sampling rate of 45 Hz (1000/22) for all players on both teams (Frencken et al., 2010, Leser et al., 2011, Ogris et al., 2012). The LPM systems have the ability to detect live data, which is a benefit over optical tracking systems, where post-match analysis is required. The LPM systems detect speed, acceleration and distance metrics based off the change in the transponder from one position to the next. A further benefit of some of the LPM systems, is the ability to detect ball movement, providing a tactical tool to assist with analysis on the space utilization between players, their movement and interactions with the ball and passing options (Ogris et al., 2012).

The usage of LPM technology has been popular in football with numerous studies attempting to quantify football specific movements (Ogris et al., 2012, Frencken et al., 2010, Leser et al., 2011, Stevens et al., 2014). When comparing football specific movements over a pre-determined course to speed gates, RF technology underestimated distance covered by an error (%CV) of -1.6%. Absolute and relative speeds were also underestimated with a margin of error (%CV) of -1.3% and -3.9% respectively (Frencken et al., 2010). However these results were from only 3 participants, and the validation against timing gates is questionable (Frencken et al., 2010).

Expanding from this study, Ogris, leser et al. determined the accuracy of a RF based LPM system; which measured the differential time of flight (TOF) from transponders to base stations, against VICON; a 8 camera infrared-based motion capture system, and has been considered "gold standard" for human movement analysis (Ogris et al., 2012). A number of runs were performed at pre-determined zones to reflect walking through to sprinting speeds, as well as 2 v 2, 2 v 3 and 3 v 3 Small-Sided Games (SSGs) (Ogris et al., 2012). The mean absolute error of the LPM system for distance detected was 23.4 ±20.7 cm, which was inclusive of all runs performed and the SSG movements (Ogris et al., 2012). The ability of LPM to accurately detect accelerations and decelerations, along with other running movements over varying speeds and including 180° and 90° change in direction was also assessed with reference to VICON system in a later study (Stevens et al., 2014). The accuracy for distance (%CV) was underestimated by an average of -2%, average speed was also underestimated by -0.8%, whilst peak speed was on average only slightly overestimated by 0.6% (Stevens et al., 2014). The movements that involved a change in direction, were also underestimated which was considered a function of the delay between the actual position and the estimated position of the transponder (Stevens et al., 2014). Further, peak acceleration was overestimated (0.88 $m.s^{-1}$ bias) with the general conclusion that accelerations performed below ~1.5 $m.s^{-1}$ may not be accurately measurable using LPM (Stevens et al., 2014). This is a substantial limitation of the LPM as many football specific actions contributing to global load require accelerations, such as change in direction and occur in confined areas on the pitch and hence naturally are performed over lower velocities. Whilst LPM appears sufficient for time-motion analysis and is able to be used both indoors and outdoors, there is inconclusive evidence as to whether it provides the most appropriate tool for quantifying global external football load. This is due to the limitation in detecting movements performed at lower accelerations, and inability to account for load through external contacts, and non-velocity movements.

2.2.4 Global Positioning System (GPS) Technology

The final tracking system that will be explored in detail is Global Positioning System (GPS) technology, which is commonly utilised in team sports, including many football teams around the globe. The GPS system works via satellites (27 orbiting the earth) emitting radio frequency signals to an individual receiver, worn by each athlete (Schutz and Herren, 2000, Schutz and Chambaz, 1997, Larsson, 2003). Each satellite contains an atomic clock, which transmits time signals (at the speed of light) to the receiver. The signal time is then multiplied by the speed of light to determine distance through trigonometry based on the lag time of the signals between the receiver and the satellite (Larsson, 2003, Schutz and Herren, 2000, Schutz and Chambaz, 1997). Quantifying 2D movement requires signals transmitted from three satellites and 3D position can be determined from calculated distance to at least four satellites (Schutz and Herren, 2000, Townshend et al., 2008, Larsson, 2003, Schutz and Chambaz, 1997, Scott et al., 2016b). Receiver displacement is determined via a sophisticated algorithm; the Doppler shift, which calculates the rate of change of the RF signals (Schutz and Herren, 2000). The

GPS has the benefit of providing simultaneous real-time data on multiple athletes (Portas et al., 2010). Initial validation of GPS to quantifying exercise was performed comparing the velocity during walking and running (0.6 – 5.6 $m.s^{-1}$) and cycling (5.6 – 11.1$m.s^{-1}$) movements to velocity detected via chronometry (using a metronome). Whilst the speeds detected via GPS were closely correlated to the measured speed (r = 0.99), suggesting high validity (Schutz and Chambaz, 1997), the study had a substantial limitations of the validation approach and only collecting data from one participant. Expanding on initial validation work from Schutz and Chambaz, GPS technology has been used to quantify external load in team sport activity since 2003 (Aughey, 2011). The use of GPS is now widespread in both applied and research settings (Aughey, 2011, Cummins et al., 2013, Coutts and Duffield, 2010, Malone et al., 2017a, Scott et al., 2016b). Advancements in GPS technology have improved the frequency rate of sampled data (over ten-fold higher) as well as improved processing capacity. Initial units sampled at 1 Hz (1 sample per second), with now the most commonly used sampling at 10 Hz (10 samples per second), and newer units available sampling at 15 Hz (15 samples per second) (Scott et al., 2016b, Johnston et al., 2012). Increased sampling frequency increases the updates of live data points which improves the quality and increases the validation of movement detected (Aughey, 2011). Indeed, numerous studies have explored in further detail the comparisons of validity and reliability between 1 Hz, 5 Hz, 10 Hz and 15 Hz sampling frequencies over various running speeds, distances and football specific movements (Portas et al., 2010, Johnston et al., 2012, Rampinini et al., 2015, Castellano et al., 2011, Johnston et al., 2013, Coutts and Duffield, 2010, Jennings et al., 2010, Akenhead et al., 2014). It is not the particular focus of this thesis to explore in entirety specific comparisons of reported values of validity and reliability of the different sampling frequency over the differing activities monitored in different team sport. An overall consensus though is that 1 Hz units were accurate and reliable for detecting total distance and peak speed, but not for higher-intensities and underestimated more complex movements including changes in direction (Jennings et al., 2010, Coutts and Duffield, 2010, Portas et al., 2010). It appears a similar trend with 5 Hz units, that they display an acceptable level of validity and reliability for detecting total distance, speed, and number of efforts performed over lower speeds, but reduced levels of validity and reliability are evident when measuring higher-speed movements (>6.9 $m.s^{-1}$) (Johnston et al., 2012). The error of measurement of 1 Hz and 5 Hz has been identified as a range between 2 – 25%, compared to timing gates (Coutts and Duffield, 2010, Portas et al., 2007, Edgecomb and Norton, 2006, MacLeod et al., 2009). Further, a similar error range (% CV) of 4% for slower movement speed to 30% for faster movement speed was identified comparing 1 Hz and 5 Hz units against VICON (Duffield et al., 2010).

However, an increase in sample frequency to 10 Hz has provided two to three times more accurate data compared to 5 Hz units (Varley et al., 2012), with substantial improvements in the reliability of detecting total distance, time spent and number of efforts performed low-speed running (0 – 3.9 $m.s^{-1}$) and high-speed running (3.9 – 5.6 $m.s^{-1}$) in both 10 Hz and 15 Hz units (<10% CV) (Johnston et al., 2014b). The validity and reliability of 10 Hz + still remains reduced during high-speed running, as well as for quantifying changes in directions over lower velocities and within confined spaces (Johnston et al., 2014b, Jennings et al., 2010, Coutts and Duffield, 2010, Aughey, 2011, Duffield et al., 2010). Furthermore any movements that are performed in a horizontal displacement, including contacts with other players, as well as football specific movements, are not detected via GPS (Howe et al., 2017). This is an important consideration which will be re-introduced later.

2.2.5 Integration of multiple systems

One of the biggest confounding factors in monitoring football players during training and match play, until recently, has been a restriction imposed by FIFA on wearing tracking devices in competition match play (abolished July 2015). Many football stadiums, used by elite teams, primarily in the European Premier League now have installed optical tracking software, which teams have the option of utilising during match play. Teams have thus had to integrate and use different systems, for example GPS technology during training with optical tracking or LPM during match play (Buchheit et al., 2014). This has allowed for a substantial amount of quantification, using various systems on the external load of footballers during training and match play, with a focus on velocity based metrics of distances and speeds.

2.3 Quantifying activity profile

Given the convenience and accessibility of multiple monitoring systems, a plethora of research has quantified the activity profile of team sport athletes, including defining football players "typical" activity during match play and training. Comparisons have been identified for example between football leagues (Dellal et al., 2011a), competition levels (elite to sub elite or domestic) (Bradley et al., 2010), playing positions (Bloomfield et al., 2007, Reilly and Thomas, 1976, Di Salvo et al., 2007) and training drills to match-play (Casamichana et al., 2012). Further, comparisons between halves, as well as different timing periods (e.g. 15 minute blocks) across a match are useful for identifying reduced player performance (Bloomfield et al., 2007, O'Donoghue, 2002, Reilly et al., 2012, Burgess et al., 2006).

Total distance has been subdivided into differing velocity threshold bands (up to 6) to broadly categorise various movement patterns (walking; zone 1 through to high-intensity running and sprinting; zone 4+) athletes perform during training and match play (Cummins et al., 2013, Malone et al., 2017a). However, speed zone categorization has utilised default, or absolute zones, rather than relative or individualised zones per player or positional group (Reardon et al., 2015). The issues with the differences in velocity bands, can be over- or underestimation of the requirements of playing positions, and also difficulty in comparing playing positions from another club or competition (Reardon et al., 2015). A broad summary of different leagues and the common velocity measures of match data expressed per playing position is displayed below; Table 2.1. This includes total distance and classifications of high-speed running and sprinting distance. To provide a comparison of activity profile to other team sports played with the ball, AFL and Rugby League have been included. The table demonstrates the substantial variability in pre-determined velocity bands for classifying "high-intensity" and "sprint" activity, which is a further limitation of relying on GPS to track activity profile, which will be expanded upon below. Given the sporadic nature of key moments during football match play including possession changes, creating and defending goal scoring opportunities, categorising movement into pre-determined time periods or speed thresholds lacks the sensitivity to determine fluctuations in or peak running intensities (Di Salvo et al., 2009, Delaney et al., 2017, Carling et al., 2008). Different moving averages have been proposed as an appropriate method for detecting the most demanding periods during match play, and the subsequent declines in performance following those peak periods (Delaney et al., 2017, Delaney et al., 2016a, Delaney et al., 2015, Di Mascio and Bradley, 2013).

Table 2.1 Total distance, relative distance, high intensity and sprint distance covered in elite football playing positions, with AFL and Rugby league included for comparison.

Authors	League	Position	Total Distance (m)	Relative Distance ($m \cdot min^{-1}$)	High-Intensity (m)	Sprinting (m)
(Di Salvo et al., 2007)	Spanish Premier League	Central Defenders	10627 ±893	118.07 ±9.92*	397 ± 114 (5.3 – 6.4 $m.s^{-1}$)	215 ± 100 (>6.4 $m.s^{-1}$)
		Wide Defenders	11410 ±708	126.78 ±7.87*	652 ± 179 (5.3 – 6.4 $m.s^{-1}$)	402 ± 165 (>6.4 $m.s^{-1}$)
		Central Midfielders	12027 ± 625	133.63 ±6.94*	627 ± 184 (5.3 – 6.4 $m.s^{-1}$)	248 ± 116 (>6.4 $m.s^{-1}$)
		Wide Midfielders	11990 ± 776	133.22 ±8.62*	738 ± 174 (5.3 – 6.4 $m.s^{-1}$)	446 ± 161 (>6.4 $m.s^{-1}$)
		Forwards	11254 ± 894	125.04 ±9.93*	621 ± 161 (5.3 – 6.4 $m.s^{-1}$)	404 ± 140 (>6.4 $m.s^{-1}$)
(Vigne et al., 2010)	Serie A	Defenders	9698.76 ± 2901.48	118.37 ± 12.03	791.34 ± 286.91 (4.4 – 5.3 $m.s^{-1}$)	902.15 ± 406.09 (>5.3 $m.s^{-1}$)
		Midfielders	8943.00 ± 3992.23	129.01 ± 9.80	827.48 ± 376.81 (4.4 – 5.3 $m.s^{-1}$)	875.29 ± 438.64 (>5.3 $m.s^{-1}$)
		Forwards	7733.77 ± 3650.38	115.38 ± 6.89	562.70 ± 278.69 (4.4 – 5.3 $m.s^{-1}$)	846.07 ± 454.86 (>5.3 $m.s^{-1}$)
(Dellal et al., 2011a)	La Liga	Central Defenders	10496.1 ± 772.0	116.62 ±8.58*	226.1 ± 53.8 (5.8 – 6.7 $m.s^{-1}$)	193.6 ±64.6 (>6.7 $m.s^{-1}$)
		Wide Defenders	10649.7 ±786.2	118.33 ± 8.74*	284.8 ± 54.7 (5.8 – 6.7 $m.s^{-1}$)	248.9 ± 77.4 (>6.7 $m.s^{-1}$)
		Midfielders – Central Defensive	11247.3 ±913.8	124.97 ±10.15*	279.6 ± 66.2 (5.8 – 6.7 $m.s^{-1}$)	203.3 ± 76.4 (>6.7 $m.s^{-1}$)
		Midfielders – Central Attacking	11004.8 ±1164.2	122.26 ±12.94*	278.0 ± 61.0 (5.8 – 6.7 $m.s^{-1}$)	222.2 ± 66.5 (>6.7 $m.s^{-1}$)
		Wide Midfielders	11240.8 ±761.8	124.90 ±8.46*	310.6 ± 67.0 (5.8 – 6.7 $m.s^{-1}$)	250.8 ± 71.5 (>6.7 $m.s^{-1}$)
		Forwards	10717.7 ±901.4	119.09 ±10.02*	288.6 ± 56.1 (5.8 – 6.7 $m.s^{-1}$)	260.0 ± 72.6 (>6.7 $m.s^{-1}$)
(Dellal et al., 2011a)	FA Premier League	Central Defenders	10617.3 ±857.9	117.97 ±9.53*	240.8 ± 63.9 (5.8 – 6.7 $m.s^{-1}$)	208.5 ± 69.4 (>6.7 $m.s^{-1}$)
		Wide Defenders	10775.3 ±645.9	119.73 ±7.18*	270.1 ± 55.0 (5.8 – 6.7 $m.s^{-1}$)	263.0 ± 69.9 (>6.7 $m.s^{-1}$)
		Midfielders – Central Defensive	11555.6 ±811.2	128.40 ±9.01*	319.1 ± 67.7 (5.8 – 6.7 $m.s^{-1}$)	245.8 ± 77.9 (>6.7 $m.s^{-1}$)
		Midfielders – Central Attacking	11779.5 ±705.9	130.88 ±7.84*	334.0 ± 60.7 (5.8 – 6.7 $m.s^{-1}$)	267.3 ± 64.2 (>6.7 $m.s^{-1}$)
		Wide Midfielders	11040.8 ±757.0	122.68 ±8.41*	298.0 ± 62.4 (5.8 – 6.7 $m.s^{-1}$)	259.2 ± 84.9 (>6.7 $m.s^{-1}$)
		Forwards	10802.8 ±991.8	120.03 ±11.02*	299.8 ± 63.7 (5.8 – 6.7$m.s^{-1}$)	278.2 ± 78.0 (>6.7 $m.s^{-1}$)
(Wehbe et al., 2014)	Australian National Soccer League	Defenders	9642.58 ± 659.71	104.65 ±7.37	2039.30 ± 663.18 (>4 $m.s^{-1}$)	589.07 ± 279.02 (>5.5 $m.s^{-1}$)
		Midfielders	10769.58 ±514.98	116.09 ±4.88	2611.96 ± 420.35 (>4 $m.s^{-1}$)	716.73 ± 250.85 (>5.5 $m.s^{-1}$)
		Forwards	10164.80 ±1124.75	111.85 ±13.15	2333.54 ± 417.07 (>4 $m.s^{-1}$)	707.54 ± 75.38 (>5.5 $m.s^{-1}$)
(Varley et al., 2014)	Australian Rules Football	Overall average	12620 ± 1872	129 ± 17	1322 ± 374 (≥5.5–10 $m.s^{-1}$)	328 ± 164 (≥7– 10 $m.s^{-1}$)
(Varley et al., 2014)	Rugby League	Overall average	6276 ± 1950	97 ± 16	327 ± 168 (≥5.5–10 $m.s^{-1}$)	50 ± 50 (≥7– 10 $m.s^{-1}$)

*** $m.min^{-1}$ have been estimated based on total distance divided by 90 minutes match time as $m.min^{-1}$ were not provided in original text.**

2.3.1 Limitation of velocity derived metrics

The 2D measurement systems, including optical tracking, LPM and GPS are limited in their ability to only detect a change in x; medio-lateral and y; anterior-posterior positions over time (straight-line movements). A footballer's typical activity profile, involves multi-directional movements performed with and without the ball, interacting with other players utilizing space around the pitch. During a match, although a footballer covers a substantial amount of lower intensity running and walking, around 10% of the overall distance is achieved through sprinting and repeat sprint efforts (Mohr et al., 2003, Carling et al., 2008, Rampinini et al., 2009, Stølen et al., 2005). High-intensity efforts are associated with game-deciding activities, such as attacking or defending a goal scoring opportunity (Stølen et al., 2005, Vigne et al., 2010), with a substantial variation in high-speed activity between players from match-to-match (Carling et al., 2016, Gregson et al., 2010). This variation is due to a number of confounding variables including playing formation (Bradley et al., 2011), level of competition (Bradley et al., 2013, Bradley et al., 2010), and quality of opposition (Rampinini et al., 2007a) to name a few.

Given the sporadic nature of multi-directional football movements, total load cannot be determined by distance in isolation. Further, distance does not account for the global movements that require acceleration and deceleration with changing direction, and physical contacts associated with ball movements and competing for space and position with other players (Arrones et al., 2014, Barrett et al., 2016a, Carling et al., 2008). Interestingly, it has also been identified that whilst isolated running performance was decreased towards the later stages of a match, this was not accompanied with a reduced frequency of skill-related performance (Carling and Dupont, 2011). Thus, it appears, and somewhat not surprisingly, that the combination of movements, and match related factors dictates the activity profile of footballers, and the resultant fatiguing effects. When performing sprint running, the athlete's acceleration of the centre of mass (COM) is determined by body mass and key external forces acting on the body: ground reaction force (GRF), gravitational force and wind resistance (Hunter et al., 2005, Kawamori et al., 2013). The GRF is the result of accelerations performed in the 3 movement vectors; vertical, anterior-posterior and medial-lateral (Kawamori et al., 2013, Hunter et al., 2005). Given the association with accelerating and decelerating when performing high-speed running (Osgnach et al., 2010, Akenhead et al., 2013), categorising high-speed running in isolation in to pre-determined velocity bands, will also not account for the acceleration and deceleration involved prior to and following maximal efforts. Further, this will miss any associated load through GRF and acceleration movements, when performing high-intensity work and changing direction. A team sport such as football also involves a substantial amount of non-running based demands through body contacts and ball control, which again will not be accounted for if using isolated velocity metrics. Therefore, velocity based measures and pre-determined bands substantially underestimate global load. The underestimation occurs through the inability to detect multi-directional movements involving accelerations, when changing direction over lower velocities within confined spaces, and the force produced in the 3 vectors associated with GRF (Barrett et al., 2014, Duffield et al., 2010, Castellano et al., 2014, Dalen et al., 2016, Carling et al., 2008, Kawamori et al., 2013). Pre-determined speed ranges (for example 5 or 15 minute periods) also mitigate the peak intense moments during match play. It has thus been identified that modelling the running intensity as a function of time (for example 1 minute rolling through to 10 minutes) encapsulates the changes in peak intensities allowing for training drills to be compared to the relative peak intensities performed during match play (Delaney et al., 2016a, Delaney et al., 2017).

2.3.2 Quantifying activity profile utilizing accelerometers

To overcome the limitations of velocity-based metrics, the use of high sample frequency (100 Hz) accelerometers are an alternative. Accelerometers have been integrated into GPS technology, providing a more global measure of external load (Cummins et al., 2013, Boyd et al., 2013, Coutts and Duffield, 2010, Aughey, 2011, Boyd et al., 2011). Accelerometers have the ability to detect movements performed in all 3 vectors, including the z (vertical) axis, which allows for precise and accurate measurement of accelerations and decelerations, from which changes in direction and total body contacts can be calculated (Cummins et al., 2013, Boyd et al., 2013, Cormack et al., 2014). One of the GPS providers, Catapult Sports™, has developed a specific algorithm: PlayerLoad™ utilizing accelerometer data. PlayerLoad™ is calculated by the squared root of the sum of the squared instantaneous rate of change in acceleration in each of the three movement vectors (x, y and z), divided by 100 (Boyd et al., 2011) and expressed in G-force (shown below).

$$\text{Player load} = \sqrt{\frac{\left(a_{y1} - a_{y-1}\right)^2 + \left(a_{x1} - a_{x-1}\right)^2 + \left(a_{z1} - a_{z-1}\right)^2}{100}}$$

2.3.3 Application of PlayerLoad™ for quantifying team sport activity

Accelerometer derived PlayerLoad™ encompasses all movements performed, providing a more indicative measure of activity profile. This is especially relevant in a sport like football where players perform rapid changes in direction and “non-conventional” sport-specific movement patterns in both possession and re-gaining possession of the ball. Further, given the substantial quantity of sprints performed by a footballer, accelerometers are more appropriate for quantifying the GRF produced when accelerating (Kawamori et al., 2013). Whilst PlayerLoad™ appears to provide a global metric accounting for multi-plane accelerations, the utilization of PlayerLoad™ for quantifying external load during football training and match play is somewhat limited.

The usefulness of accelerometers to quantify activity profile in other team sports including AFL, basketball, rugby and netball has been explored in more detail (Boyd et al., 2013, Montgomery et al., 2010, Howe et al., 2017, Cormack et al., 2014, Mooney et al., 2013a, Colby et al., 2014, Lovell et al., 2013). Previous utilization of PlayerLoad™ has determined variation in activity profile when comparing levels of competition (Cormack et al., 2014), playing position (Barron et al., 2014, Cormack et al., 2014), phases of the season (Colby et al., 2014), training to match load (Montgomery et al., 2010, Boyd et al., 2013), and also throughout different periods of football match play (Barrett et al., 2016a). PlayerLoad™ provides an advantageous measure of external load, given the ability of accelerometers to detect accumulated movement in all directions. This is important to assist with load management, as well as determining recovery rate. However, whilst appearing to be a superior measure to velocity based metrics, quantifying different levels of external load utilizing PlayerLoad™ and the impact on post-match recovery in elite footballers is unknown.

Differences have been observed relative to playing position in the accumulation of PlayerLoad™ during football match play. More specifically, central midfielders accumulate a substantially higher PlayerLoad™ during match play than central defenders (Barron et al., 2014). Higher PlayerLoad™ in central midfielders reflects their match activity pattern associated with covering higher total distance and therefore accumulating a higher amount of associated GRF, and movement performed in the anterior-posterior direction (Scott et al., 2013a). Central midfielders also have a substantially higher contribution of the vertical (z) axis contribution to their overall PlayerLoad™, which was further associated with the increased vertical force via ground contacts through the heel strikes when running (Barron et al., 2014).

2.3.4 Derived PlayerLoad™ metrics

Expressing PlayerLoad™ relative to duration (PlayerLoad™.min^{-1}) or distance (PlayerLoad™.m.min^{-1}) is useful for identifying variations in movement intensity and efficiency. Previous exploration of relative PlayerLoad™ metrics has been with the aim of identifying changes in movement strategy that may be a cause/response of fatigue during match play (Cormack et al., 2013, Cormack et al., 2014, Mooney et al., 2013a, Barrett et al., 2016a, Barreira et al., 2017). The increase in relative PlayerLoad™; expressed over time or distance, has been previously been suggested to reflect a decrement in exercise intensity or change in efficiency, due to athletes increasing their movement over the same amount of time or to achieve the same amount of distance (Mooney et al., 2013a, Cormack et al., 2013, Barrett et al., 2016a).

During football match play, increased PlayerLoad™ per unit of distance (PlayerLoad™.min^{-1}) was observed across each 15 minute period of each half (Barrett et al., 2016a). The increased PlayerLoad™.min^{-1} across the 15 minute periods of each half was justified as reflecting the development of fatigue across the match due to the association with a decrement in movement efficiency and the periods of the match most frequently associated with injury (final 15 minutes of each half) (Barrett et al., 2016a). The reduced movement efficiency as a reflection of a 'fatigue' response and increased PlayerLoad™.min^{-1} was proposed to occur as a result of a reduction in stride length leading to increased stride frequency and foot contacts (Barrett et al., 2016a). However, the limitation of this study was the absence of an associated measure of fatigue per se to allow a comparison with the increase in PlayerLoad™ per relative distance. An alternate explanation for an increase in PlayerLoad™ per unit of distance may be an increase in accelerations, decelerations and changes in direction contributing to the relative distance covered (Dalen et al., 2016). An increased PlayerLoad™ per unit of distance may in fact be indicative of an 'end spurt' during the final periods of a half of match play, and the result of an increased activity profile rather than a manifestation of fatigue (Bradley and Noakes, 2013, Paul et al., 2015).

Even when expressed per unit of distance or time, the use of global PlayerLoad™ lacks the ability to determine the contribution of individual movement vectors that may be more responsive to determining specific changes in movement strategy that might occur in response to fatigue (Dalen et al., 2016, Cormack et al., 2013, Mooney et al., 2013a). The impact of pre-match neuromuscular fatigue has changed the movements and efficiency to obtain the same physical output during match play (PlayerLoad™.min^{-1}) in AFL players (Mooney et al., 2013a). Further, a state of pre-match neuromuscular fatigue resulted in a meaningful change in the relationship between PlayerLoad™.min^{-1}, and the amount of relative high-intensity running, but was not observed with the relative distance (m.min^{-1}) (Mooney et al., 2013a). It was concluded that AFL players, may be able to produce a similar overall work output (PlayerLoad™.min^{-1}) with the presence of fatigue, but the contribution of movements to generate the overall PlayerLoad™ are altered, and performed at a lower intensity (Mooney et al., 2013a). The proposal of altered movement to contribute to the accumulated PlayerLoad™.min^{-1} occurring from the individual movement vectors, specifically an increase in the lateral or vertical components (Mooney et al., 2013a), warrants further exploration. It was further identified that AFL players experiencing neuromuscular fatigue appear to undergo changes to their mechanical efficiency and movement patterns, which received a simultaneous reduction in coach rating (how effectively they performed their role assigned to them) of performance (Mooney et al., 2013a). The impact of neuromuscular fatigue driving changes in movement performance and efficiency, appeared to be the result of the contribution of the individual (x, y and z) movement vectors. The individual movement vectors: x (anterior-posterior), y (medio-lateral) and z (vertical) reflect accelerating and decelerating (x), side rotation through the hip and pelvis when changing direction (y) and vertical ground reaction forces (z) (Barrett et al., 2014, Barrett et al., 2016b). The percent contribution of these individual vectors have been used to reflect changes in match performance and associated movement actions when fatigued in AFL, netball, rugby and football (Cormack et al., 2013, Cormack et al., 2014, Mooney et al., 2013a, Mooney et al., 2011, Barrett et al., 2016b, Dalen et al., 2016, Barrett et al., 2016a, Gabbett, 2015).

A state of pre-match neuromuscular fatigue reduces the contribution of the vertical (z) axis to the overall PlayerLoad™.min^{-1} in AFL players during match play (Cormack et al., 2013). The decrement in the z axis was associated with a reduction in vertical ground reaction forces and changes in vertical stiffness as a result of an altered running style resulting in increased low speed running and less acceleration (Cormack et al., 2013). The impact of a change in movement efficiency, highlighted through the difference in the z axis contribution to match accumulated PlayerLoad™.min^{-1} resulted in a lower rating of performance from coaching staffs (Mooney et al., 2013a, Mooney et al., 2011).

Other accelerometer based metrics include: PlayerLoad™$_{SLOW}$; reflective of movements performed at a low velocity <2 m.s^{-1} (Boyd et al., 2013), useful for quantifying body contacts resulting from wrestling and grappling movements in rugby (Gabbett, 2015, McLaren et al., 2016). PlayerLoad™$_{2D}$ which excludes the vertical (z) vector and provides a measure of movements performed in the anterior-posterior and medio-lateral planes used to quantify changes in direction (Davies et al., 2013).

Accelerometer based metrics have the ability to determine changes in movement patterns, and movement efficiency through detecting multi-plane movements. Changes in accelerometer derived metrics as an impact of suppressed neuromuscular function has been identified in AFL, however, further exploration of this concept in elite football is warranted. Along with the exploration of the change in external load metrics as a result of load and fatigue, there is also the important consideration of how the training process and fatigue impacts individual athletes' internal response.

2.4 Determining an athlete's internal load

Adaptation to the training process is reliant on not only quantifying external load, but importantly, knowledge of an athlete's response to the external load. This psycho-physiological response is referred to as internal load (Halson, 2014, Jaspers et al., 2017, Weaving et al., 2014, Impellizzeri et al., 2005). It has been well established that an athlete's internal response can substantially differ from the same external load at any given time, due to various influences (Gallo et al., 2015, Johnston et al., 2015). Monitoring the interaction between both external and internal load is thus crucial for identifying the fitness and fatigue responses throughout the training process, on an individualised level (Halson, 2014, Akubat et al., 2014, Bartlett et al., 2017, Aughey et al., 2016, Scott et al., 2013a).

A number of different measures have been utilised to determine an athlete's internal response to prescribed load. These are considered objective, for example: heart rate (HR), hormonal and immunological responses or subjective, for example: rating of perceived exertion (RPE), wellness questionnaires (Scott et al., 2013a, Alexiou and Coutts, 2008, Moreira et al., 2012) and assessment of cognitive function and sleep hygiene (Halson, 2014, Fullagar et al., 2015, Nédélec et al., 2015, Juliff et al., 2015, Thornton et al., 2016).

2.5 Objective measures of internal load

2.5.1 Heart Rate

Heart rate (HR) response is one of the most traditional and commonly used measures of internal stress response. The appeal of using HR is the direct reflection of the autonomic nervous system (ANS), with a heightened HR during steady state exercise associated with increased sympathetic and simultaneously reduced parasympathetic activity (Halson, 2014, Daanen et al., 2012, Borresen and Lambert, 2008a, Al Haddad et al., 2011). A linear relationship exists between HR and oxygen consumption ($\dot{V}O_{2max}$) with an increased work rate during sub maximal intensity exercise, representing a greater demand of oxygen to provide for a increased amount of work performed (Arts and Kuipers, 1994, Lamberts et al., 2004, Freedson and Miller, 2000, Eniseler, 2005) Given the association between a higher HR reflecting an increase in exercise intensity (for example the parallel with $\dot{V}O_{2max}$) during steady-state exercise, specific HR ranges have been developed that correlate to intensity ranges, based on an individual's maximal performance (Hopkins, 1991, Halson, 2014, Achten and Jeukendrup, 2003). Whilst useful for reflecting increased steady state workload intensity, a major limitation of HR in quantifying the intensity of intermittent activity, such as football, is a lag in HR to a quick change in intensity (Achten and Jeukendrup, 2003, Stagno et al., 2007). Football movements are diverse and sporadic, performed over various intensities within the one session or match (Eniseler, 2005), and given HR response is limited to this activity, an average session HR may provide limited insight into an athletes response to the load. The exploration into differing HR responses, including variation in resting HR, the heart rate recovery (HRR) following a standardised test (for example a submaximal run) and the post-standardised test heart rate variability (HRV) have been proposed with specific application to football (Buchheit et al., 2010b, Buchheit et al., 2012, Buchheit et al., 2007, Buchheit, 2014b). This is shown below in Figure 2.4.

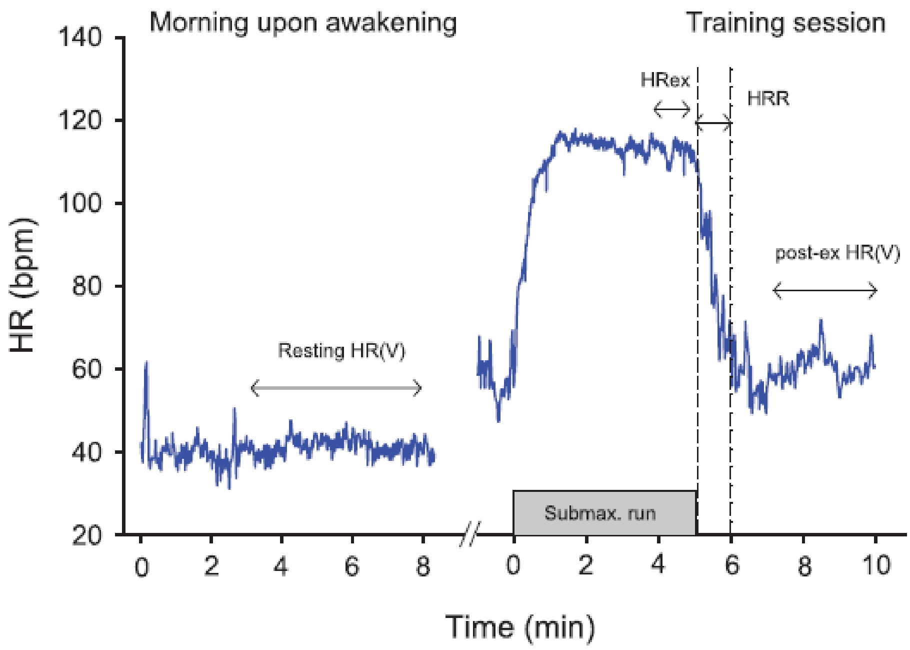

Figure 2.4 Various measures of Heart Rate (HR) response throughout the day. Heart Rate during exercise; HRex, Heart Rate Recovery (HRR) over 60s and heart rate variability (HRV). Reproduced from (Buchheit, 2014b).

2.5.2 Heart rate recovery (HRR) and heart rate variability (HRV)

Measures of heart rate recovery (HRR) and heart rate variability (HRV) reflect cardiovascular adaptation to training and match load, under control of the autonomic nervous system (ANS) (Buchheit et al., 2011, Buchheit et al., 2012, Oliveira et al., 2013, Stagno et al., 2007, Akubat and Abt, 2011, Foster et al., 2001, Buchheit et al., 2007, Borresen and Lambert, 2008a, Achten and Jeukendrup, 2003, Daanen et al., 2012). Given the ANS interaction with all other physiological systems, changes in HR response may reflect the capacity of the body's tolerance to exercise induced stress (Borresen and Lambert, 2007). Measures of HRR and HRV are useful across all team sports, however, given the focus of this thesis the specific application of these measures to football will be described in further detail below.

The heart rate recovery (HRR) defines the rate at which the HR declines following an exercise bout (Daanen et al., 2012, Halson, 2014, Borresen and Lambert, 2007), identified via a number of standardised protocols (Borresen and Lambert, 2007, Lamberts et al., 2004). A simple test to determine athletes HRR in the applied setting is a 5 minute – 5 minute (5'-5') protocol, with previous usage with football athletes (Buchheit et al., 2010b, Buchheit et al., 2012, Buchheit et al., 2011, Buchheit et al., 2010a). The 5'-5' test involves 5 minutes of sub-maximal running (previously reported at a speed of 2.5 $m.s^{-1}$ to minimize any anaerobic contribution (Buchheit et al., 2010b). Following the 5 minute run, athletes come to a stationary position, which has been previously been reported as a seated position on the side of the pitch for a further 5 minutes (Buchheit et al., 2010b, Buchheit et al., 2011, Buchheit et al., 2012). The HRR was calculated the most common way - the difference between HR at the end of the exercise, and the HR recorded 60 s in to the 5' recovery period (Buchheit et al., 2007, Buchheit et al., 2010b). Identification of the post exercise parasympathetic reactivation due to different training modalities of high-intensity intermittent training (HIT) compared to repeat sprint (RS) efforts, was identified in adolescent handball players (n = 17) over a 9 week period (Buchheit et al., 2008). It was identified that the training stimulus of HIT was more effective at improving fitness (through repeat sprint ability; RSA), reduced the post-exercise HRR and increased the HRV (Buchheit et al., 2008). This association demonstrated improved post-exercise parasympathetic function as a result of improved physical performance which was effectively reflected with the use of HR markers within the training program (Buchheit et al., 2008).

However, whilst overall patterns have been observed within a team to a reduced HRR and increased HRV with different training interventions, it is important to note that the relationship between HRR and training status is variable for each athlete as a determinant of age, ambient temperature, intensity of the preceding workload, and fitness levels. The relationship between HRR and training status has shown that increased HRR reflects increased training status before reaching a stable plateau, and also decreasing in response to a reduction in training volume (Halson, 2014, Buchheit et al., 2010b, Daanen et al., 2012).

Another common marker associated with training status is HRV. The HRV identifies the oscillating intervals between heart beats. The time between consecutive heart beats is referred to as the RR interval. The HRV is calculated by log-transforming the root mean square of the difference in successive RR intervals (Achten and Jeukendrup, 2003, Al Haddad et al., 2011, Buchheit and Gindre, 2006, Oliveira et al., 2013). An athlete's HRV is used to provide feedback on ANS activity when measured in the same state either resting or post-exercise (Plews et al., 2013, Oliveira et al., 2013, Buchheit et al., 2012, Bricout et al., 2010, Flatt et al., 2016, Buchheit and Gindre, 2006). In response to exercise load, a higher HRV was associated with a positive adaptation to endurance training, whereas decreased HRV reflected a negative adaptation (Plews et al., 2013). However, in elite and well-trained athletes factors including genetics, tolerability to training stress and a heightened fitness capacity result in a bell-shaped trend between fitness and HRV (Plews et al., 2013, Iwasaki et al., 2003). Increased HRV exists in response to moderate training load, and then the turning point to a downward trend of HRV with further intensified training load (Plews et al., 2013). The HRV to varying load intensities differs between athletes warranting the use of individualised HR monitoring. Improvements in football player HRV occurred in response to intensified training load in the pre-season phase, which was synonymous with increased fitness measured via repeat-sprint ability (RSA) and yo-yo intermittent recovery tests (Oliveira et al., 2013). However, tapering training load throughout the training cycle has impacted and reduced HRV. Therefore, identifying HRV from single observations may be misleading, due to the fluctuations in training load. Changes in HRV over averaged weekly or 7 day rolling average provide a more appropriate representation of individual changes, and determining the smallest worthwhile change (TE) within an athlete to compare their relative values, would provide the most appropriate feedback (Plews et al., 2013, Al Haddad et al., 2011). One of the limitations of the derived HR measures for monitoring internal load is that it is a reflection only of central ANS and CV responses (Buchheit et al., 2011). Further, whilst HR has been used to determine workload intensity relative to $\dot{V}O_{2max}$, it can be highly variable and has limitations with intermittent sports such as football. A singular averaged or peak response of a HR metric, lacks the ability to breakdown differences in workload intensity throughout a training session or match play, which limits the usefulness for determining changes in performance relative to differing intensity. Further, whilst HRR and HRV reflect an overall change in fitness and performance, this testing approach does require additional set-up and timing to perform the test and collect data. Whilst yet to be explored, there is the consideration that standardised drills may be able to detect changes in movement efficiency when fatigued. Changes in movement efficiency may provide a more efficient means of detecting changes in athlete's response to training and competition load and provide a useful marker of intensity.

2.5.3 Training Impulse (TRIMP)

As an alternate to the overall session average HR, integrating HR with session duration has been proposed to provide a global measure of training intensity and referred to as training impulse (TRIMP) (Herman et al., 2006, Banister et al., 1975a, Fitz-Clarke et al., 1991). The initial TRIMP was calculated using session average or total HR (summation of every heart rate point) multiplied by the duration of the session

(Banister, 1991). However, this original TRIMP calculation utilizing average or session HR lacked the ability to distinguish varying exercise intensity across the session (Foster et al., 2001, Stagno et al., 2007). To overcome the limitation of a global average session HR, a number of HR zones were devised, with the accumulated time spent in each zone multiplied by varying weighting factors (Stagno et al., 2007). The use of differing HR zones reflects the levels of increased exercise intensity (Foster et al., 2001, Stagno et al., 2007). Foster proposed a TRIMP model where 5 linear incremental HR zones corresponded to10% increments of athlete's peak HR (starting at 50% - 60% of max; level 1) (Foster et al., 2001). However, the incremental range of 10% of maximal HR was considered to be too broad to identify individualised anaerobic threshold when determining intensity (Stagno et al., 2007). The range of 10% also has implications given the metabolic stress may not be constant between athlete's exercising within the same range of percentage of maximal HR (Stagno et al., 2007, Katch et al., 1978). Adaptations of Foster's TRIMP model utilizing HR zones have been applied to account for differences in training intensity. This has included 3 zones in well-trained long distance runners (competing 5,000 m and 9,000 – 12,000 m cross-country distances), corresponding to exercise performed below ventilatory threshold (VT), between VT and respiratory compensation threshold (RCT) and high-intensity exercise performed above the RCT (Esteve-Lanao et al., 2007). The TRIMP model approach to specifically reflect altered physiological responses and individual variance in anaerobic threshold was a modification of the 5 zones used to determine TRIMP based around two key blood lactate values; 1.5 $mmol.L^{-1}$ and 4 $mmol.L^{-1}$ (set for zones 2 and 4). The other 3 zones were set at the fractional elevation of exercising heart rate curved against the change in blood lactate (ΔHR - $[La^{-}]_{b}$ curve) at a width of 7% around 2 and 4 (Stagno et al., 2007). Each zone was assigned a weighting factor, based on the regression equation of the ΔHR - $[La^-]_b$ curve (Stagno et al., 2007, Akubat and Abt, 2011). In English Premier Division hockey players, a weekly modified TRIMP ($TRIMP_{MOD}$) was calculated with HR zones corresponding to two breakpoints on a typical blood lactate response curve; lactate threshold (1.5 $mmol.L^{-1}$) and the onset of blood lactate accumulation (4 $mmol.L^{-1}$) (Stagno et al., 2007) The $TRIMP_{MOD}$ was sensitive to changes in $\dot{V}O_{2max}$ and speeds covered at a lactate threshold (4 $mmol.L^{-1}$), but not to high-intensity running or peak running speed (Stagno et al., 2007). In team sport athletes intermittent exercise alters the ΔHR - $[La^-]_b$ relationship, and thus the TRIMP weightings (Akubat and Abt, 2011). The ability of TRIMP to reflect intensified load during high-intensity intermittent sports is thus limited due to the inability to detect and reflect muscular movements associated with running, changes in direction and speed. This is due to the TRIMP calculation relying on the HR, which is a internal response measure, and as previously described has limitations in reflecting intermittent high-intensity running (Stagno et al., 2007).

Whilst TRIMP may be useful for reflecting overall changes in fitness capacity as a reflection of work load performed relative to $\dot{V}O_{2max}$ or lactate threshold, it appears insufficient for activity that is intermittent in nature and quantifying total load accumulated through changing directions which is synonymous with football activity. This is the result of the calculation, being that TRIMP utilises HR which reflects purely ANS and cardiovascular responses (Buchheit et al., 2011). Whilst the ANS does interact and control the other physiological systems, HR in isolation doesn't reflect physiological load response per se. As an indicator of the internal physiological stress response, the exploration into patterns of a number of key hormones, enzymes and metabolites has been performed across a variety of sports, and exposure to varying load, which will be explored below.

2.5.4 Biochemical Markers

A number of enzymes, hormones and metabolites can by identified from bodily fluids including blood, saliva and urine, providing useful markers of internal stress response following physiological load. Commonly reported markers from blood include: creatine kinase (CK) (Russell et al., 2015, Hunkin et al., 2014, McLellan et al., 2010, Russell et al., 2016) and lactate (La^-) (Beneke et al., 2011, Borg et al., 1987, Ojasto and Häkkinen, 2009, Coutts et al., 2009), whilst hormonal analysis of cortisol and testosterone (Aubets and Segura, 1995, Balsalobre-Fernández et al., 2014, Brownlee et al., 2005, Edwards et al., 2006, Elloumi et al., 2003) is commonly determined via both serum and saliva.

2.5.5 Blood markers

Football specific activity including repeated changes in direction, accelerating and decelerating and body contacts results in muscle damage and an associated inflammatory response (Nédélec et al., 2012, Thorpe and Sunderland, 2012). One of the most commonly assessed blood markers used to reflect cardiac or skeletal muscle damage is creatine kinase; CK (McLellan et al., 2010, Hunkin et al., 2014, Russell et al., 2016, Scott et al., 2016a, Coelho et al., 2016, Baird et al., 2012, Hortobagyi and Denahan, 1989, Clarkson and Ebbeling, 1988). Following intense exercise, CK is leaked in to the bloodstream due to cell membrane rupture, evidenced with muscle damage (Russell et al., 2015, Young et al., 2012, Russell et al., 2016, Lazarim et al., 2009, Thorpe and Sunderland, 2012). Creatine kinase is a cytoplasmic enzyme that is involved with energy metabolism (Coelho et al., 2016). More specifically, CK acts as a catalyst for the reversible phosphorylation of creatine, utilizing adenosine triphosphate (ATP) to create phosphocreatine (PCr) and adenosine diphosphate (ADP), and yield energy supply to the working muscles (Szasz et al., 1976). Given the involvement of CK in energy metabolism, it has however been questioned if the increase in serum CK is actually the consequence of increased metabolic activity, reflecting a disruption in energy control processes or an alternate molecular reaction mechanism, rather than the degree of muscle damage *per se* (Baird et al., 2012).

There has been a generalised pattern of response of CK to training and match play in team sports including AFL and rugby, however different responses have been observed as a result of individual variability, coupled with the sport-specific activity profile variability and associated response to increased high-intensity eccentric loading or body load and contacts (Young et al., 2012, McLellan et al., 2010, Cunniffe et al., 2010, Russell et al., 2016, Scott et al., 2016a, Tofari et al., 2017, Ispirlidis et al., 2008). The general pattern of response of CK following exercise however follows an immediate post-match increase, with highest post-match values observed around 24 – 48 hours after match play (between 70% - 250% of baseline) and returning to baseline between 48 to 120 hours (Ispirlidis et al., 2008, Andersson et al., 2008, Twist et al., 2012, Twist and Highton, 2013, McLellan et al., 2011, Russell et al., 2015). A number of different factors can influence the timing of individual responses of CK, including exercise modality and the magnitude of eccentric loading contributing to greater muscle damage, exposure to body contacts, individual's time-course of inflammation as well as genetic variations, gender and age related factors (Baird et al., 2012, Hortobagyi and Denahan, 1989).

Baseline values in the general population of CK are within the range of 35 – 175 $U.L^{-1}$, although this is highly varied across individuals due to a number of reasons, including injury, genetic factors, change in fitness status and physical activity, with ranges from 20 to 16,000 $U.L^{-1}$ have been observed (Baird et al., 2012). In American footballer's, a range of 200 – 450 $U.L^{-1}$ has been reported (Hoffman et al., 2002, Kraemer et al., 2009, McLellan et al., 2010) whilst following rugby union match play, CK was increased to

1,023 $U.L^{-1}$ (Gill et al., 2006). Such a drastic increase in CK post rugby match play was considered to be a function of increased muscle damage due to the body contacts through tackles (Thorpe and Sunderland, 2012, Gill et al., 2006).

With specific reference to the response of CK to football match play, an 84% increase in CK concentration was observed post-match compared to pre in semi-professional players (Thorpe and Sunderland, 2012). Whilst in professional football players, CK was increased 24 hours following match play (334.8 ±107.2 $U.L^{-1}$), with values remaining elevated for 48 hours, suggestive of substantial muscle damage for up to 48 hours following match play (Russell et al., 2015). However, concentrations of CK were not influenced by match or position (determined by match / position x time interactions), and there was no inclusion of activity profile data to determine the driving force contributing to the CK response (Russell et al., 2015).

Given the proposed response of CK to exercise load, the potential utilization of CK to provide an indirect indicator of overload through associated muscular adaptation across a football season was explored (Lazarim et al., 2009). However, the study by Lazarim et al. in Brazilian players, was limited to monthly assessment of CK, therefore limiting the interpretation of any dose-response relationship between oscillating weekly load and CK response.

Increased pre-match CK was associated with small decrements in match performance in AFL players, suggestive of incomplete recovery and muscular damage resulting from the pre-match training load (Hunkin et al., 2014). Measures of CK and peak power output (PPO); determined from countermovement jump (CMJ) testing on a force platform, were assessed concurrently at 24 and 48 hours post football match play, to identify the interaction between load, neuromuscular and biochemical responses (Russell et al., 2016, Shearer et al., 2017, Russell et al., 2015). However, the pre-match timing for baseline CK and PPO has varied between studies from < 12 hrs (Russell et al., 2015) to 24 hours prior (Russell et al., 2016, Shearer et al., 2017) to match play. The timing of test performance may have implications for comparing post-match measures, as a pre-match value may be higher than usual as a result of the training load performed leading in to match play, which has not been considered in prior work. Factoring in the timing of test performance, it was however observed that PPO was reduced at 24 and 48 hours compared to pre-match baseline (237 ± 170 watts; W and 98 ± 168 W respectively), with a coinciding increase in CK (334.8 ± 107.2 $U.L^{-1}$ and 156.9 ± 121.0 $U.L^{-1}$ respectively) (Russell et al., 2015). Whilst this suggests a coupling between muscular damage and decreased power production for at least 48 hours following football match play, further exploration is warranted into the fatigue response to match play relative to varying load exposure and playing positions.

Simplistically, blood lactate $[La^-]_b$ has been used to estimate energy production through the anaerobic glycolitic contribution to metabolism and useful as a determinant of exercise intensity (Coutts et al., 2003, Santos-Silva et al., 2017). There has been a substantial range of $[La^-]_b$ values observed across different sporting codes, which has been considered to reflect the variation in activity profiles, fitness levels, emotional stress, timing of measurement collection and environmental conditions (Coutts et al., 2003). Regardless of the individual variance, anaerobic threshold has been identified to occur at the $[La^-]_b$ value of 4.0 $mmol.L^{-1}$ (Bangsbo et al., 2007, Beneke et al., 2011). Given the nature of football match play involving phases of lower intensity activities, there is a large contribution of energy from aerobic metabolism (around 90%), however, the intermittent bursts of high-intensity activity involve anaerobic glycolosis, which produces lactate (Santos-Silva et al., 2017, Bangsbo et al., 2007). Whilst an athletes lactate threshold is highly individualised (Eniseler, 2005), during football match play, average $[La^-]_b$ values have been identified to fall within the range of 2 to 10 mmol.L^{-1}, with some individual athletes recording values as high as 12 mmol.L^{-1} (Bangsbo et al., 2007, Ekblom, 1986, Bangsbo et al., 1991, Krustrup et al., 2006, Bangsbo, 1994, Currie et al., 1981). There has been proposal that increased $[La^-]_b$ reflects an increased amount of high-intensity running or tackling and body load performed (Coutts et al., 2003). Differences in an athlete's response may be a function of individual variance, or the collection site; for example common sites for blood withdrawal include the fingertip or earlobe (Foster et al., 2001).

Whilst the measures of CK and $[La^-]_b$ have provided useful measures of the expected rate of recovery in muscular damage, and exercise intensity in football players, their biggest limitation is the requirement of a blood sample to determine these measures. Considering the logistics of the analysis requirement of blood sampling, this is a factor that needs to be considered within the training program. Given it would be a requirement to identify the teams' response to training drills or the session and the associated timing and disruption to do so, this approach does not equate to a very practical one, casting doubts on the effectiveness of CK as a marker of recovery. This coupled with some uncertainty over whether an increased CK truly reflects muscle damage, or the response of the role it plays in energy metabolism, again provides limitations to CK analysis.

An alternative marker of the internal physiological response to load, has been the exploration of stress-responding hormones including cortisol and testosterone. Further, given the potential stress and procedure involved with blood analysis, as an alternate, saliva has been effective in determined key hormonal values.

2.5.6 Salivary markers

Saliva has become a preferable substance for detecting a range of hormones, proteins, nucleic acids and electrolytes including the aforementioned testosterone and cortisol. Saliva is non-invasive and does not place any additional stress on the athletes which may impact results, particularly of the stress responsive hormone cortisol. Saliva contains certain molecules found in the blood, which enter via diffusion, filtration and/or active transport (Pfaffe et al., 2011). Saliva can detect the concentration of lipid-soluble unbound or “free” steroids including cortisol and testosterone, which accurately reflects the unbound plasma concentrations (Vining et al., 1983b, Pfaffe et al., 2011). Saliva is formed using an active energy-consuming process where sodium is pumped into the end-pieces of the salivary gland, creating osmotic based pressure differences between blood and saliva. As a result, water flows through the tight junctions (between acinar cells) into the saliva (Vining et al., 1983b). The salivary concentration of lipid-soluble unconjugated steroids (cortisol, estriol, testosterone, progesterone etc.) travel to the saliva intracellularly and do not depend on salivary flow rate (Vining et al., 1983b). In addition to active transport, plasma components may enter the saliva via two possible mechanisms: Intracellular diffusion – whereby lipid-soluble unconjugated steroids diffuse into the acinar cells and then diffuse out the other side in to the saliva. They may also pass through the cells lining the ducts of the glands (Vining et al., 1983b). Cortisol enters saliva intracellularly diffusing through the salivary gland cells. The concentration between unbound fraction of cortisol in plasma and saliva is maintained due to a high diffusion rate, which is also independent of salivary flow rate (Vining et al., 1983b, Pfaffe et al., 2011). Between 500-1500 mL of saliva is produced daily in healthy adults, equating to around 0.5 $mL.min^{-1}$ (Pfaffe et al., 2011).

2.5.7 Testosterone

Testosterone is an androgenic anabolic steroid that has a substantial role in protein synthesis (Michailidis, 2014, Kraemer, 1987, Kraemer et al., 1988, Kraemer et al., 2009, Vingren et al., 2010, Sutton et al., 1973). Testosterone is primarily produced by the gonads, with a small amount also produced in the adrenal glands (Vingren et al., 2010). Gonadal testosterone production occurs under the control of gonadotrophin releasing hormone (GnRH) which is released by the hypothalamic-pituitary-gonadal (HPG) axis (Vingren et al., 2010, Sollberger et al., 2016). Under stressful conditions, testosterone, mediated by the androgen receptors suppresses the function of the hypothalamic-piuitary-adrenal (HPA) axis (Viau, 2002, Herman et al., 2016). Just under half of the testosterone present in the blood binds to a carrier protein; sex hormone binding globulin (SHBG), with the other half a separate carrier protein albumin. Around 2% remains unbound or "free" which can be identified through salivary analysis (Vingren et al., 2010).

At the musculature level, testosterone promotes hypertrophy as a result of stimulation of protein synthesis and inhibiting protein degradation (anti-catabolic effect) (Vingren et al., 2010). Increased testosterone has also been associated with preparatory, aggressive and competitively dominant behaviour increasing assertiveness and vigour (Kraemer et al., 2004, Argus et al., 2009, Martínez et al., 2010, Crewther et al., 2013, Gaviglio et al., 2014a). The anticipatory rise in pre-competition testosterone has a positive impact on match outcome (Crewther et al., 2013), occurs prior to competition at a home venue (Carré et al., 2006), but has also has a negative correlation with performance in elite junior hockey players (Carré et al., 2006). Therefore, it appears that there may be a turning-point of heightened testosterone driving the aggressive and assertiveness to improve competitiveness, but also too much that may be detrimental to performance.

Whilst an increase in testosterone can assist with counteracting the catabolic effects of cortisol it appears that a reduction in testosterone does not allow for anabolic stimulation of protein catabolism or immune suppression to preserve glycogen concentration in the muscle and therefore cannot overcome the effects of a hormone like cortisol (Kraemer et al., 2004). An increased catabolic environment, which may arise with a lower testosterone response was associated with a reduced ability to generate force and associated lower limb strength (Kraemer et al., 2004). Testosterone displays a circadian rhythm, with highest values observed in the morning with a steady decline across the day (Guignard et al., 1980, Teo et al., 2011).

The response of testosterone to match play and training in team sports has varied considerably. At the semi-professional level, a 44% increase in testosterone was identified post-match compared to pre (Thorpe and Sunderland, 2012), however this response was not followed across the days following. In AFL players, whilst there was no immediate post-match measure of testosterone analysed, when compared to pre-match, *unclear* or *trivial* post-match responses (24 hours – 96 hours) in testosterone were observed (Cormack et al., 2008a). The post-match testosterone response was also compared to 48 hours pre-match, with substantial reductions observed at 72 hours and 96 hours post-match (Cormack et al., 2008a), which is suggestive of the impact of post-match training load manipulation. In response to international level Rugby match play, testosterone decreased by around 20% (Elloumi et al., 2003). Further work in Rugby has identified that whilst match-play induced a small increase in salivary testosterone, this was not substantially different to the baseline measure, 24 hours pre-match (McLellan et al., 2010). However, given that there was a substantial 47% decrease in testosterone immediately pre-match compared to the baseline, this may have represented an artificially higher value as a result of pre-match training, which would negate any post-match responses that were lower than baseline. The association between a change in hormonal recovery and subsequent match performance has been considered previously in AFL and football players (Cormack et al., 2008b, Kraemer et al., 2004).

Identifying the impact of training volume on testosterone has again highlighted mixed results. A period of intensified high-intensity training during a competitive football season caused a substantial decrease in testosterone (Filaire et al., 2001), caused a non-substantial change throughout a professional level football season (Filaire et al., 2003), and similarly throughout a competitive AFL season in response to varying training load (Cormack et al., 2008b). In contrast, a four week progressive overload period in well-trained young tennis players had no clear change in testosterone levels (Gomes et al., 2013). The inconsistencies between results as a function of variability in timing of collection of testosterone (4 times during the season vs. weekly) has made the identification of the pattern of response of testosterone to variable training and match load difficult. However, when identifying the response of testosterone across differing training microcycles between match play in Rugby (5, 7 and 9 days), there was no clear change with testosterone being highly varied (McLean et al., 2010). With no clear pattern of the overall team response of testosterone to different training load exposure, this exemplifies athlete's individual variability and therefore the investigation of the pattern of response per positional groups relative to training and match load would be interesting. When testosterone response was linked to the match outcome, an elevation in the hormone in response to strength training workouts was linked to winning games in professional Rugby players. The association between a positive adaptation response from the training load or reflective of the recovery from previous match play, requires further exploration in elite football (Crewther et al., 2013). It appears that the usage of salivary biomarkers such as testosterone may be useful for identification of athlete readiness and recovery from previous weekly training load (Crewther et al., 2013) however, more evidence is required in identifying the response to skills based training sessions and match play. Furthermore, it is unclear how testosterone interacts with other markers of recovery and individual variation with the impact on match performance in elite footballers. There is also a lack of understanding of the time-course of response of testosterone following football match play. Whilst it appears that an increase in pre-match testosterone is associated with increased competitiveness, assertiveness and vigour, it is unclear in elite footballers the impact of pre-match testosterone on match performance. However, little is known on the interaction between testosterone responses to varying levels of load exposure, relative to playing position in elite football, which warrants further exploration.

2.5.8 Cortisol

Cortisol is a catabolic hormone (Viru and Viru, 2004, Aubets and Segura, 1995, Kirschbaum and Hellhammer, 2000, VanBruggen et al., 2011), responsive to the combination of both physical and psychological stress (Aubets and Segura, 1995). cortisol is produced in the adrenal cortex, where it is synthesised and secreted by the adrenal glands, under the regulation of the adrenocorticotropin hormone (ACTH) from the anterior pituitary gland (Kirschbaum and Hellhammer, 2000, Bunt, 1986, Michailidis, 2014). Cortisol is released into the blood stream where it is transported throughout the body primarily by binding to carrier proteins including cortisteroid-binding globulin (CBG), erythrocytes and albumin (Kirschbaum and Hellhammer, 2000, Vining et al., 1983a). The remaining biologically active cortisol, that doesn't bind to a carrier (around 2-15%) is considered “free” or unbound (Kirschbaum and Hellhammer, 2000). The unbound or “free” cortisol is light in molecular weight and lipophilic, which enables it to enter cells through passive diffusion. Free cortisol can then be assessed in all bodily fluids, with serum, and saliva the most commonly analysed (Kirschbaum and Hellhammer, 2000). Salivary and free plasma cortisol concentration have a high correlation (r = 0.97) (Thuma et al., 1995), with salivary cortisol reflecting unbound serum cortisol (McLellan et al., 2011, Cadore et al., 2008, Vining et al., 1983a). As well as being a less invasive collection process (Pfaffe et al., 2011), cortisol determined via saliva also accurately reflects serum un-bound levels independent of saliva production or flow rate (Kirschbaum et al., 1992, Aubets and Segura, 1995, Vining et al., 1983a, Gatti and De Palo, 2011). An additional benefit of using saliva to identify cortisol is it is free from the saturation of CBG which cortisol binds to in the blood for transportation. The benefit being that CBG displays highest saturation in the morning which artificially affects the change in cortisol responses measured via serum (Vining et al., 1983a).

Cortisol is described as an adaptive hormone due to its involvement with numerous key physiological functions including fat, carbohydrate, protein and electrolyte metabolism (Kirschbaum et al., 1992, Michailidis, 2014). As cortisol is a glucocorticoid it’s involvement in carbohydrate metabolism results from enhancing free fatty acid mobilization, protein synthesis and gluconeogenesis; generation of glucose from non-carbohydrate based substrates such as lactate, glycerol and glucogenic amino acids (Bunt, 1986, Kraemer et al., 2009, Michailidis, 2014, Kirschbaum et al., 1992). Given its involvement in the above described process, which inhibits the immune system, cortisol is described as a catabolic hormone (Michailidis, 2014). Increased protein catabolism is associated with a state of fatigue (Martínez et al., 2010).

Fluctuations in cortisol follow a circadian rhythm, with peak values in the morning around 08:00 – 1000 followed by a steady decrease across the day (Aubets and Segura, 1995, Shephard and Shek, 1997, Filaire et al., 2001). Determining the magnitude of change in cortisol thus appears to be relative to the "baseline" value and the time of day this occurs (Thuma et al., 1995). The circadian impact on baseline values helps explain why there have been differences across previous research in the pattern of response to varying loads, with increased, no change and decreased responses all reported (Thuma et al., 1995, Dimitriou et al., 2002). Along with circadian variance, given the stress responsive nature of cortisol values are impacted not only as a result of exercise-induced stress but also broad life stressors which in combination lead to substantial individual variance of this hormone (Kirschbaum et al., 1992).

Given the individual variance and circadian rhythm of cortisol, appropriate determination of the pattern of response reflecting training and match load, requires the magnitude of change relative to an appropriate baseline, representing a reasonably "stress-free" state. Collection of cortisol at the same time of day, preferable first thing in the morning will also ensure consistency when comparing post responses to pre (Thuma et al., 1995, Dimitriou et al., 2002). The response of cortisol was markedly higher in a group of male swimmers, when comparing pre values; 4.20 ±1.74 $nmol.L^{-1}$ to post values; 7.54 ± 4.29 $nmol.L^{-1}$ of an exhaustive treadmill test compared with pre values; 6.59 ± 3.92 $nmol.L^{-1}$ to post values; 9.65 ± 6.22 $nmol.L^{-1}$ of competition (Aubets and Segura, 1995). The increased values pre and post competition highlight the additional psychological stress in a competitive environment (Aubets and Segura, 1995, Elloumi et al., 2003). Following an immediate increase to competition load, cortisol was generally returned to baseline values between 1.5 – 4 hours following competition (Kraemer et al., 2009) However, variance has been identified in the timing of post-match cortisol across differing sporting codes, and competitions. Cortisol increased immediately in response to match load in AFL and rugby (international level) (Elloumi et al., 2003, Cormack et al., 2008a). In contrast, rugby (League) players had a post-match reduction in cortisol lasting 48 hours (McLean et al., 2010). Further variability has been observed in the pattern of response within the same sport where one group of rugby players reported a decreased cortisol compared to baseline for four days (Elloumi et al., 2003), whilst the opposite effect of a gradual increase for four days also been found (McLean et al., 2010). The post-match increase in cortisol in AFL players was followed by a substantial reduction at 96 and 120 hours post-match, which appeared to be a result of the training stress response in the days following match play (Cormack et al., 2008a). Whilst hormonal measures provide a global response to match play, there has been no information provided on how varying levels of match load impacts the pattern of post-match cortisol response.

Accounting for the relationship between training load and cortisol across a competitive season has again revealed mixed results according to sport and sampling technique (blood versus saliva). Whilst an elevation in cortisol was reported across a competitive football season, (Kraemer et al., 2004), blood analysis was limited to only 6 occasions throughout the season. The response of salivary cortisol reflected intensified training load across a four week progressive-overload period in tennis athletes and was also closely correlated to their perceptions of stress (determined via Daily Analysis of Life Demands for Athletes (DALDA) questionnaire (r = 0.71) (Gomes et al., 2013). In the same study with tennis players, and further in basketball athletes, cortisol had a close and positive correlation to internal load (r = 0.64 and 0.75 respectively) (Gomes et al., 2013, Moreira et al., 2012). However, the interaction between internal load and cortisol response in elite football players is unknown and requires investigation.

Salivary cortisol response determined across a separate football season (spanning 9 months) revealed no clear change in cortisol (Filaire et al., 2001). However, testing was also limited to only four occasions. A more comprehensive weekly assessment of salivary cortisol throughout a competitive Australian Football League (AFL) season identified that compared to baseline (36 hours prior to the first round match), cortisol was reduced in all training weeks (Cormack et al., 2008b). However, timing of cortisol sampling was varied (between 72 hours and 144 hours post match), and the baseline may have been artificially heightened as a result of prior training load, resulting in the consequential lower cortisol throughout the season (Cormack et al., 2008b).

The cortisol response appears to vary across different windows of load exposure, as noted across a rugby season, where a more acute window (5 days) resulted in a lower cortisol response compared to 7 days and 9 days (McLean et al., 2010). A reduction in load identified through a taper period has however, shown varied results in swimmers (Mujika et al., 1996b).

In regards to the anticipatory effect of competition stress and the impact on a stress responsive hormone like cortisol, a number of different studies have explored the impact of home advantage and pre-competition anxiety states on performance (Carré et al., 2006). Whilst pre-match cortisol was higher when players competed at their home ground, this was not influential on pre-game somatic anxiety or match performance (subjective 4 point rating scale from poor [1] to very good [4]) (Carré et al., 2006).

The aforementioned studies in team sports have however averaged individual athlete responses across the team, therefore limiting the knowledge of even how positional groups vary in their cortisol response to match and training load, warranting further investigation. For consistency, and to account for the circadian impact, baseline values appear to be best identified in the morning. The overall impact of varying levels of exposure to match load on cortisol response is unknown in team sport athletes. Further, an effective time-course of post-match cortisol response and the impact on subsequent match performance is unknown in elite football, warranting further investigation.

2.5.9 Testosterone:Cortisol Ratio

Given the opposing responses of testosterone (anabolic) and cortisol (catabolic), the two hormones has been presented together as the testosterone:cortisol ratio (T:C) to show the relative changes in the bodies anabolic-androgenic activity (Kraemer, 1987, Thorpe and Sunderland, 2012, Elloumi et al., 2003).

A reduction in the T:C by more than 30%, has been proposed to reflect a state of overtraining (Viru and Viru, 2004, Thorpe and Sunderland, 2012). A heightened T:C ratio is suggestive of a state of anabolism, and a greater contribution of testosterone, and when there is the drop below 30%, this reflects a greater contribution of cortisol and thus a state of catabolism (Filaire et al., 2001, Kraemer et al., 2004)

However, specifically in football players, a reduction in T:C, synonymous with a catabolic environment following high-intensity training was not associated with reduced performance or overtraining (Filaire et al., 2001). Whilst in rugby and AFL players, a lower T:C was observed pre-match, compared to 24 hours pre, which suggested a pre-match catabolic environment, given the observation of a heightened cortisol and slightly reduced testosterone (McLellan et al., 2010, Cormack et al., 2008a). Although a lower T:C ratio was associated to increased training load and performance capacity (Elloumi et al., 2003), the impact of a change in T:C on subsequent match performance is unknown.

A reduced T:C ratio further reflects increased proteolysis; breakdown of proteins into smaller polypeptides or amino acids, and decreased protein synthesis. Whilst it has been suggested that the differences in hormone secretion are interconnected with changes to the neuromuscular system (Crewther et al., 2009b), both the neuromuscular and hormonal responses have been viewed independently, and therefore further investigation is warranted. When considering the response to load, whilst measures of internal stress response are important, a further consideration is athletes' individual perceptual response. Subjective measures of internal load

2.5.10 Rating of perceived exertion

One of the most important indicators of athletes' response to training and match play is their own perception. Individual rating of perceived exertion (RPE) provides a global measure of the psycho-physiological response to physical and mental load (Borg, 1998, Borg et al., 1987, Borg, 1990). The RPE is an outcome of cues taken from the central nervous system, cardiovascular and respiratory systems and peripheral joints and muscles (Borg, 1990). The RPE displays an overall linear relationship to increased exercise intensity (Noble et al., 1983, Wallace et al., 2009, Foster, 1998). The original RPE scale was designed using a 15-grade scale with numbers 6-20 displayed and anchored to written cues relating to intensity from "no exertion at all"; 6 to "maximal exertion"; 20 (Borg, 1970, Borg, 1985). The 15-grade scale has been modified to a category ratio (CR-10) scale, where numbers 0-10 are anchored to the written cues of 0 "nothing at all", to 10 "extremely strong" (Borg, 1990). The basis of the RPE scale has further been specified for response to specific exercises and in specific populations – such as walking/running, cycling and weight training, for adults and children which is referred to as a OMNI (omnibus) scale; Figure 2.5 where pictures are used in combination to the verbal cues to assist participants or athletes with deciphering their perception of effort, with a visual feedback cue (Utter et al., 2004, Robertson, 2004).

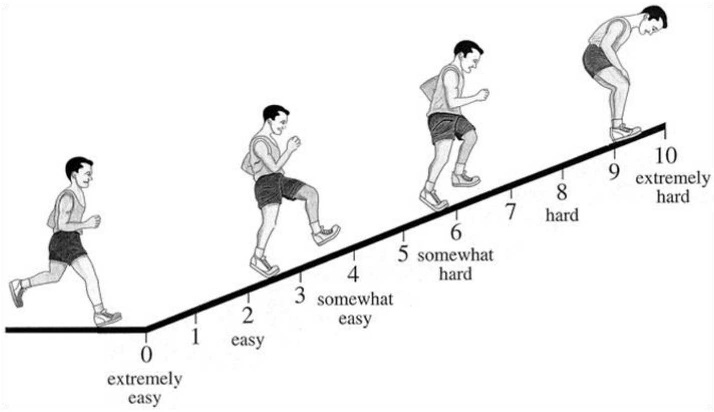

Figure 2.5 Omni Rating of Perceived Exertion (RPE) scale. Reproduced from Utter et al., (2004).

To determine session internal load, the RPE (CR-10 scale) is multiplied by total duration (in minutes) to give an overall session RPE (sRPE) (Foster et al., 2001, Foster, 1998, Halson, 2014). The sRPE approach has been closely correlated to HR zones for quantifying exercise intensity during football training (range from $r = 0.54 - 0.78$) (Borresen and Lambert, 2008b). However, a lower correlation was noted between sRPE and HR during short-duration, high-intensity football drills (Borresen and Lambert, 2008b, Halson, 2014). Whilst a global rating of perceived exertion is extremely useful, one of the limitations of a sRPE, is the oversimplification of the psych-physiological response to load, which may be insufficient for determining if the perception of effort has been driven from predominately physiological or psychological response (Weston et al., 2015). Given this consideration, in AFL, differential RPE's have been explored including: local (leg-based), central (breathlessness) and a rating of the overall match physical exertion and technical demand (Weston et al., 2015). The interaction between RPE values and external GPS and accelerometer-based metrics was also identified. The biggest association (moderate effect) was identified between the GPS derived high-speed running (absolute and relative), relative total distance, total metabolic power and relative high power distance and the local (leg-based) RPE (Weston et al., 2015). The leg-based RPE was also given the highest rating by players, reflecting the impact of peripheral sensations contributing to the overall match RPE in AFL players (Weston et al., 2015). The beneficial usage of differentiating RPE is allowing for the monitoring of what has had the largest contribution to effort perception and the association to match activity profile (Weston et al., 2015) Whilst there was no clear association between the accelerometer derived metrics and differential RPE, this was surmised as the differences in between-subject running mechanics during match play (Weston et al., 2015). A limitation of the differential RPE study with AFL players was a small window of data collection (9 matches) and providing data on the overall team, where individual responses, even differences within positional groups were observed but not accounted for. However, it was concluded that integrating both external and internal load metrics provides the greatest evaluation of any dose-response relationship during team sport match play. As a general consensus acknowledging that the sRPE is an extremely useful and beneficial tool for encompassing the global response to training and competition load, it does not account for the specific contributing factors to that rating, and whether it has been derived to a greater extent from the physiological load or psychological load. To expand upon this, the current psychological state of an athlete can have a substantial influence on the RPE value, and will drive differences in the perception of physiological stimulus (Little and Williams, 2007). Simplified daily ratings or more in-depth questionnaires can be effective for assessing alterations to athletes general wellness or psychological state (Halson, 2014).

2.5.11 Wellness and psychological assessment

Individualised wellness and psychological state questionnaires are used within team sport as a simplified quantification of an athlete's internal response to loading experienced during training and match play on a daily basis (Halson, 2014, Jones et al., 2017, Buchheit et al., 2013, Gastin et al., 2013b). The appeal of wellness ratings is the ability to identify how players are recovering and responding to the stress and demands of training and match load, which is vital for the preparation of subsequent match performance (Montgomery and Hopkins, 2013). More comprehensive and in-depth questionnaires including REST-Q sport (Jones et al., 2017, Kellmann and Kallus, 2001), Daily Analysis of Life Demands for Athletes (DALDA) and Profile of Mood States (POMS) are frequently used (Morgan et al., 1987, Terry and Lane, 2000, Leunes and Burger, 2000). The above questionnaires have been used alongside athlete burnout and distress questionnaires (Raedeke and Smith, 2001, Main and Grove, 2009) to identify the impact of load on athletes. The RESTQ-Sport contains 76 items, with a smaller 52-item version available providing a comprehensive quantitative assessment of the assessment of the frequency of stress and recovery activities throughout the prior 72 hours, which provides an appropriate indication of athletes response to their most recent load (Kellmann and Kallus, 2001). Given their extensiveness, the RESTQ-Sport is collected less frequently than a simplified wellness rating that can be performed on a more regular (usually daily) basis. The questionnaire contains 12 generalised scales (7 stress specific subscales, 5 recovery subscales), with 7 added sport-specific scales (3 relating to stress and 4 related to recovery) (Coutts and Reaburn, 2008). Within each sub scale are 4 specific questions that athletes rate on a 7-point Likert scale (Coutts and Reaburn, 2008). The RESTQ-Sport response from rugby league players (n = 20), to a 6 week overload intensified training block revealed no substantial change in the generalised stress and recovery subscales but some of the sport specific stress subscales identified an increased stress response and simultaneous decline in recovery responses (Coutts and Reaburn, 2008). A similar trend has been identified in rowing athletes (Jürimäe et al., 2004), As an alternative measure, the profile of mood states (POMS) contains 65 statements that the athletes rate on how much each one describes themselves during the previous week using a 5-point Likert scale (Curran et al., 1995, Renger, 1993). The areas covered by the POMS include depression/dejection, tension/anxiety, anger/hostility, fatigue, confusion and vigour/activity with overall results from the POMS yeilding a global distress score (Total Mood disturbance) (Curran et al., 1995, Renger, 1993). The POMS was utilised to identify a disturbance in swimmers mood as a result of overtraining and provided an early indicator of staleness that was identified by including psychological parameters (Morgan et al., 1987). Further, in swimmers (n = 9), POMS was combined with stress markers and sleep indicators to predict the chance of success or failure during competition in response to a three week pre-competition training block (Chennaoui et al., 2016). Substantial correlations were observed between increased cortisol, the psychological response in the POMS and sleep indicators in the failed performance group, which reinforced the benefit and interaction with stress, mood state and sleep influences on performance, which can be easily monitored (Chennaoui et al., 2016). Although psychometric questionnaires have been useful for early indicators of altered mental state and thus detecting indicators of maladaptation to load, given their detailed nature, more simplified daily wellness ratings have become common practice in elite sporting environments (Halson, 2014). Ratings of daily wellness have been integrated into the monitoring practices and provide beneficial as an early indication that an athlete is not tolerating the training or match load. Daily measures of assessment include ratings of: muscle soreness, feelings of fatigue, stress levels, sleep quality and mood (Gastin et al., 2013b, Buchheit et al., 2013). Different variations on wellness ratings are implemented by elite teams, with the use of a range of 4-12 items on a 1-10 Likert scale commonly utilised (Thorpe et al., 2015, Gastin et al., 2013b). The benefit of wellness ratings is they can provide an early indicator of a change in response to load – for example increased muscle soreness or fatigue, before any change in physical performance presents. The effectiveness of subjective ratings of sleep, fatigue, stress and muscle soreness predicted a state of “staleness” prior to performance declines in elite swimmers (n=19), suggesting that daily reporting of wellness may assist in early detection of overtraining allowing for load manipulation to avoid performance decrement (Hooper et al., 1995). Perceptual markers of sleep quality, fatigue and muscle soreness were also closely correlated to a change in internal RPE based load during the pre-season phase in AFL players (Buchheit et al., 2013). Wellness markers were more sensitive in detecting daily variability in training load compared to the biochemical response of cortisol. Wellness the following morning thus displayed a dose-response relationship to the prior days training load (Buchheit et al., 2013). When comparing the wellness ratings; sleep quality, muscle soreness and fatigue (Likert 1 – 7 incremental scale) in elite football players, an observed moderate-to-strong correlation was identified between high-intensity running distance (>4 $m.s^{-1}$) and ratings of fatigue (Thorpe et al., 2015). However, in contrast to the AFL study mentioned earlier, there was no substantial relationship between training load determined as high-intensity running with perceptions of sleep quality and muscle soreness (Thorpe et al., 2015). However, the study was limited to only reporting on high-intensity running to account for training and match load which would substantially underestimate the global load of football players, by not accounting for multi-directional movement and body contacts. Further, the data collection period was limited to 17 days in the football study, and therefore only providing a snapshot of the interaction between training and match load and wellness response across a season.

The use of wellness ratings provides an early indicator of an athlete's response to training and match load and can assess early indicators of a negative response to load - fatigue and maladaptation. This has important implications for load manipulation, to assist athlete's preparation and performance.

2.6 Fatigue Overview

Fatigue is one of the most crucial aspects of the training process, having both positive and negative effects. Whilst fatigue is a necessary component to drive adaptation, the implications of a prolonged fatigue state can be extremely detrimental for the performance of an athlete as well as a pre-cursor to illness and/or injury. Given the negative implications of fatigue, it is one of the most concerning areas for practitioners in sport, with particular interest on identifying the duration of neuromuscular fatigue from match play, and when is the appropriate timing for post-match training load re-introduction.

Fatigue is however, the result of complex, multifaceted and stimulus dependent interactions (Knicker et al., 2011, Enoka and Stuart, 1992, Gibson and Edwards, 1985, Barry and Enoka, 2007, De, 1984). Whilst beyond the scope of this thesis to explore the specific intricate interactions, an overview of neuromuscular fatigue and the central and peripheral models will be summarised as a main focus of this thesis.

2.6.1 Neuromuscular Fatigue

Prolonged, sustained exercise results in disturbances to the neuromuscular system (Carroll et al., 2017, Enoka and Stuart, 1992, Gibson and Edwards, 1985). Measuring neuromuscular fatigue at rest can provide feedback on the fatigue status and recovery of peripheral muscle fibres, whilst superimposed stimulation of the muscle during voluntary contractions can identify the impact of central neural drive (Carroll et al., 2017, Behm et al., 1996). Electrical or magnetic stimulation is considered the most effective way to determine the relative impact of central drive and thus the contribution of central or peripheral fatigue (Behm et al., 1996). The stimulation approach lacks practicality within team sports, given the timing to test over 20 athletes (Tofari et al., 2015). Neuromuscular impairment arising from the mechanisms responsible for force potentiation occurs as a result of repetitive stretch-shortening cycle (SSC) exercise (Ortega et al., 2010, Komi, 2000, Linthorne, 2001, Toumi et al., 2006).

Neuromuscular fatigue results in a loss of maximum force-generating capacity which may arise from various sites along the chain from the central nervous system (CNS) through to the contractile structure at the musculature (Kent-Braun, 1999). During sustained exercise, repetition of a prolonged maximal voluntary contraction (MVC) will result in the gradual decline in performance due to the working muscles natural loss in ability to sustain or produce the required workload (Carroll et al., 2017, Liu et al., 2002, Kent-Braun, 1999). The CNS controls the contraction of muscle fibres to produce force and movement by transmitting electrical impulses from the brain to the motor neurons and connected muscle fibres (Liu et al., 2002). The amount of force required to perform specific actions dictates motor unit activation, with a low force output requiring less muscle activation and therefore fewer motor units. In contrast, a high force production requires most or all of the active muscles motor units, which will require an increased rate of descending command from the CNS and resultant action potentials delivered to the motor units (Liu et al., 2002). Given the involvement and interaction between CNS and the musculature, fatigue has been divided into arising from sites proximally (central fatigue) or distally (peripheral fatigue) to the neuromuscular junction (Bigland-Ritchie et al., 1978, Kent-Braun, 1999, Amann, 2011, Shei and Mickleborough, 2013, Schillings et al., 2003, Billaut and Bishop, 2009).

2.6.2 Central and Peripheral Fatigue

The neuromuscular junction is the distinction of fatigue arising from processes proximally or distally; central and peripheral respectively. Central fatigue is caused from reduced motivation, CNS transmission, and motor unit recruitment, leading to a decreased motor drive or command (Bigland-Ritchie et al., 1978, Shei and Mickleborough, 2013, Kirkendall, 1990). Central fatigue involves several processes which contribute to a reduced central motor drive (CMD) as shown below in Figure 2.6. Factors contributing to central fatigue include reduced cortex excitability due to supraspinal factors, which leads to inadequate neural drive, and may be contributing factor to sub-optimal activation of the CMD (Shei and Mickleborough, 2013). Other supraspinal contributing factors that have been proposed to play a role in the reduction of the CMD and be the underpinning of central fatigue include increased group III and IV muscle afferents, increased brain serotonin [5-HT] or decreased brain dopamine [DA] (Shei and Mickleborough, 2013, Bailey et al., 1993, Martin et al., 2008, Taylor and Gandevia, 2008, Amann, 2011, Amann et al., 2011).

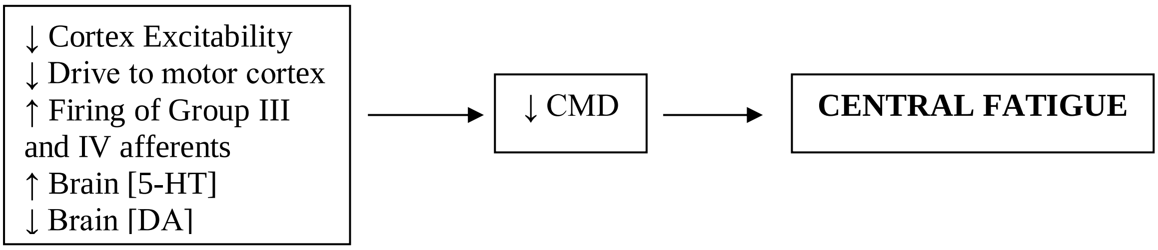

Figure 2.6 Factors contributing to central fatigue. Serotonin (5-HT), dopamine (DA) and central motor drive (CMD). Reproduced from (Shei and Mickleborough, 2013).

Peripheral fatigue conversely describes the impairment of muscle function due to impaired transmission, muscle electrical activity and activation (Strojnik and Komi, 1998, Shei and Mickleborough, 2013, Enoka and Duchateau, 2016, Carroll et al., 2017, Liu et al., 2002, Kent-Braun, 1999, Kirkendall, 1990, Taylor and Gandevia, 2008, Schillings et al., 2003). Peripheral fatigue has been observed when a decline in muscle twitch or tetanic force production occurs during peripheral nerve stimulation in the rested muscle (Taylor and Gandevia, 2008). Direct electrical stimulation of the muscle eliminates any alterations in force capacity occurring due to alterations in effort perception, motivation or fatigue caused by neural stimulation from the central nervous system (Cairns et al., 2005, Skurvydas et al., 2016, Tofari et al., 2015). Muscle force is driven by action potentials, with the rate of force development the result of recruitment and neural coding when exercising, and the stimulation frequency when artificially activating the muscle (Cairns et al., 2005). Force declines relative to the intensity of the exercise stimulus and contraction rate of the working muscles (Cairns et al., 2005). Depending on the intensity of the stimulus, the factors responsible for altering muscle fibres and resultant force production can have an immediate impact within seconds, or result in a long lasting effect referred to as prolonged low-frequency force depression (PLFFD), taking hours or even days for full recovery (Skurvydas et al., 2016, Allen et al., 2008). The decline in muscular force production, arises from several chemical interactions, with reduced free myoplasmic calcium ($[Ca^{2+}]$) concentration and a decrement in myofibrillar Ca^{2+} sensitivity having a predominant contribution (Skurvydas et al., 2016). Whilst beyond the scope of this thesis to explore in full depth the interactions between peripheral factors contributing to fatigue, a summary overview is provided below in Figure 2.7. The physiological contribution to fatigue includes decreases in circulation related arterial haemoglobin oxygen saturation (S_aO_2) and cardiac output (Q), increases in muscle metabolites including hydrogen $[H^+]$, ammonium ion $[NH_4^+]$ and inorganic phosphate concentration $[P_i]$. Reductions in energy based substrates of glucose, glycogen and phosphocreatine (PC_r) and Ca^{2+} as described above (Shei and Mickleborough, 2013).

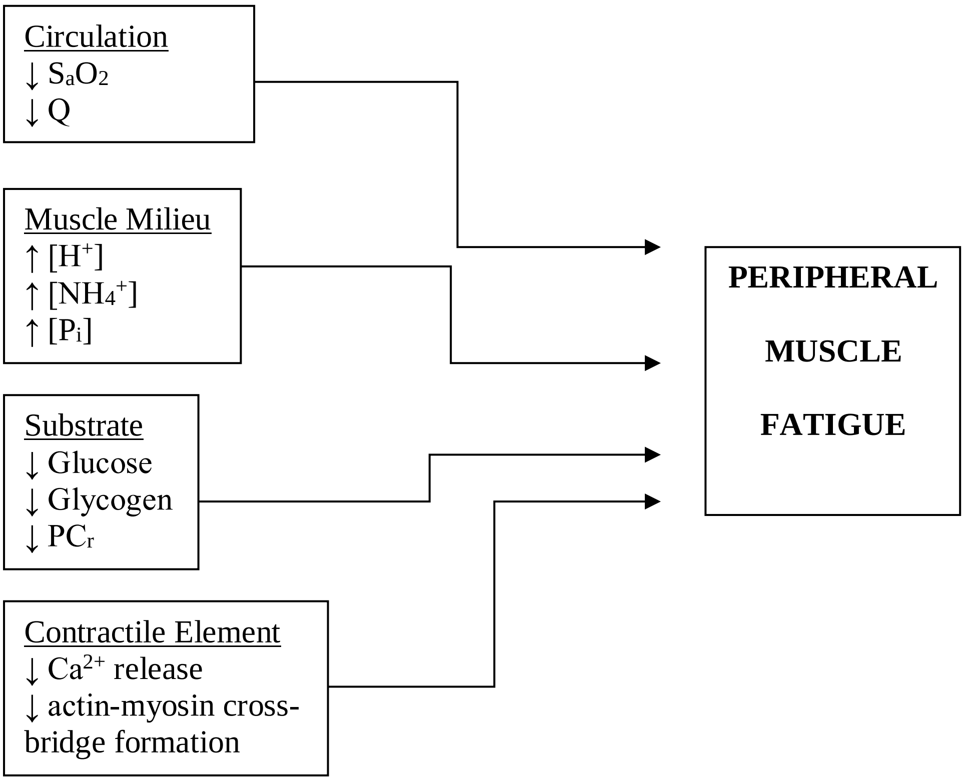

Figure 2.7 Factors contributing to peripheral fatigue. Reproduced from (Shei and Mickleborough, 2013).

To identify the contribution of fatigue; either the failure at the musculature or central drive requires electrical or magnetic stimulation to peripheral nerves and/or magnetic stimulus to the motor cortex during a maximal voluntary effort (Taylor and Gandevia, 2008, Billaut and Bishop, 2009, Tofari et al., 2015). The employment of a superimposed twitch, can identify that if additional force can be produced by stimulation during a maximal voluntary effort, fatigue is centrally driven due to motor units either not firing or recruited during the initial MVC (Taylor and Gandevia, 2008, Herbert and Gandevia, 1999, Billaut and Bishop, 2009). The use of a maximal voluntary contraction (MVC) and stimulation to the motor nerve, can determine the amount of muscle activation, via calculations including the percent voluntary activation (% VA) and central activation ratio (CAR) (Behm et al., 1996, Allen et al., 1995, Merton, 1954). Calculations of % VA and CAR has provided useful in controlled laboratory based assessments, but do require substantial time, equipment, set-up and trained professionals therefore determining the central and peripheral fatigue contributions via this assessment is impractical in the applied setting.

2.6.3 Stretch-shortening cycle

The SSC in human skeletal muscles describes the combination of the pre-stretch lengthening of the muscles (eccentric contraction) followed by the shortening (concentric) contraction phase (Kubo et al., 1999, Komi, 2000). Human locomotion movements of walking, running and jumping are prime examples of the SSC, where external forces (e.g. gravity) eccentrically lengthen the active muscle, which is followed by a concentric shortening action (Komi, 2000). The activity profile of team sports including football, involves naturally occurring repetitive movements that utilise SSC muscle function. The impact of SSC loading results in a bimodal low-frequency fatigue response causing neuromuscular impairment. The bimodal pattern of SSC-induced fatigue follows an immediate reduction in performance within the first few hours, a short-term recovery with a secondary intensified drop in performance which usually presents on the second day post-exercise (Nicol and Avela, 2006). A practical assessment of low-frequency fatigue arising from repetitive SSC activity, should be sensitive not only to the specific sporting task, but account for both the eccentric and concentric components of muscle function and force generation (Nicol and Avela, 2006, Fowles, 2006). Various forms of jump testing, which utilize SSC muscle function have therefore been integrated into team sport training programs for the assessment of low-frequency fatigue and changes in lower limb force and power production (Crewther et al., 2009a, Coutts et al., 2007, Cormack et al., 2008a, Nicol and Avela, 2006, Fowles, 2006). Calculating athletes Eccentric Utilization Ratio (EUR) can determine the effective utilization of the SSC by comparing the concentric action in isolation to an action involving both eccentric and concentric involvement. This has been done so by comparing a countermovement jump (CMJ) that includes both eccentric and concentric actions to a static squat jump (SJ) where the eccentric component is nullified (McGuigan et al., 2006). The EUR calculation compares the height achieved in the CMJ to the SJ, providing a measure of athletes ability to utilize their muscle pre-stretch, eccentric phase (McGuigan et al., 2006, Doyle, 2005). However, fatigue has been attributed to additional models which consider a greater involvement from the brain which will be explored below.

2.6.4 Alternate models of fatigue

Whilst categorizing fatigue into central and peripheral contributions may provide useful information for monitoring and treatment, the role of the brain in regulation of exercise performance has been explored with a number of alternate models including central governor theory, psychobiological model and integrative governor theory (Marcora, 2008, St Clair Gibson et al., 2018).

The central governor theory proposes the brain modulates motor unit recruitment which regulates power output, resulting in a pacing strategy to preserve physiological failure (Weir et al., 2006). In contrast to the central governor model, an alternate proposal has been the psychobiological model which is based on a motivational intensity theory (Marcora, 2008). The psychobiological model describes that fatigue occurs when the level of exertion exceeds the level of motivation (Marcora, 2008).

The final model, the integrative governor theory describes a decision making function or structure in the brain the drives a trade-off between the level of disturbance to psychological and physiological systems via a negative feedback to regulate homeostasis (St Clair Gibson et al., 2018).

Whilst several models have been proposed that consider the impact of the brain and the important integration between both psychological and physiological interactions, the aim from a team sport perspective is to be able to assess fatigue in an objective manor.

2.6.5 Monitoring neuromuscular fatigue

As lower-limb force and power is one of the key underpinning determinants for the activity profile and skills performed by team sport athletes, including football players specifically given their movement with the ball, detecting changes in these variables are important considerations and commonly assessed. Muscular mechanical power reflects the product of force acting on an object and the object's velocity (Markovic and Jaric, 2007). Maximal jump performance is utilised to test lower limb power and associated force production (Kons et al., 2017, Markovic and Jaric, 2007, Markovic et al., 2004, Bosco and Viitasalo, 1982). In team sports, especially football, jump testing provides an appropriate assessment, as an activity utilising the SSC as well as a sport-specific movement performed during training and match play (Cormack et al., 2008a, Andersson et al., 2008). Different equipment is used to assess lower limb force and power from vertical jump performance including a Vertec or yard stick, linear-position transducer (LPT), optical or rotary encoder, accelerometers, contact mat and force platform (Markovic et al., 2004, Cronin et al., 2004, Glatthorn et al., 2011, Garcia-Lopez et al., 2005, Leard et al., 2007). The force platform provides the most comprehensive assessment of jump performance, and as such is considered the "gold-standard". Whilst portable platforms are available for use within applied settings, they are expensive, and require set up following specified manufacturer's instructions to ensure quality control (Cronin et al., 2004). The usage of force platforms in applied settings has thus been limited, with alternate measures such as contact mats and LPT more commonly utilised for determining jump performance (Crewther et al., 2011).

The LPT device detects the displacement of a tethered cord (attached to either a bar, weight stack or the athletes' waist from a rotational sensor (Harris et al., 2010, Crewther et al., 2011). To determine force and power by the LPT system, requires calculations from the known velocity, which is referred to as the differentiation process (Harris et al., 2010, Crewther et al., 2011). Dividing displacement over time produces velocity, which then divided by time yields acceleration. Force can then be calculated using the equation of force = mass x acceleration, with the mass factored in as either the athlete's mass and any additional mass from a bar and weights included (Harris et al., 2010, Crewther et al., 2011). Force-time and velocity-time curves are then generated, with power estimated through the multiplication of the curves (Harris et al., 2010). Whilst the calculated peak and mean power and force, peak velocity and displacement can be reliably determined from the LPT, the measures that are time-dependent such as rate of force development and time-to-peak force, are less reliable (Harris et al., 2010, Cronin et al., 2004). When the data collected from a LPT is compared to a force platform, mean and peak force from the LPT as well as time-to-peak force display acceptable relative (ICC) and absolute (%CV) reliability (ICC >0.70 and CV <5%) (Cronin et al., 2004). However, limitations are evident with the LPT, as well as the Vertec / yardstick approach when quantifying power and force of the lower limbs, due to the involvement and contribution of upper body movement and an associated change in athlete's centre of mass (Glatthorn et al., 2011). Utilising a force platform provides a direct measure of athletes' ground reaction forces. With the force known, other metrics associated with displacement and power can thus be derived.

Two of the most commonly used jumps to determine lower limb force and power are the SJ and CMJ (Van Hooren and Zolotarjova, 2017, Markovic et al., 2004, Johnston et al., 2015, McLean et al., 2010, Owen et al., 2015, Sheppard et al., 2008). Athletes are able to produce more power and resulting outcome of jump height when performing a CMJ compared to a SJ. The CMJ is thus a much more natural technique for athletes to perform, due to the utilization of muscle activation during the initial eccentric lengthening phase resulting in a greater opportunity to generate energy and produce more power output (Linthorne, 2001, McGuigan et al., 2006).

The specific role of the quadriceps femoris and hamstrings in the initial eccentric lengthening phase of the CMJ is responsible for developing a larger force in the CMJ compared to the SJ (Kubo et al., 1999). Performing a maximal CMJ with the hands maintained on the hips restricts any upper body contribution, providing an effective performance test to overcome the limitations described above to isolate the lower limb force and SSC activity (McGuigan et al., 2006, Taylor et al., 2012a, Gathercole et al., 2015b, Cormack et al., 2008a). When performed on a force platform, which is the desired equipment to test for CMJ performance, ground reaction forces can be detected and measured, with derived measures of jump height (from flight time), power and displacement (Cormack et al., 2008c, Cormack et al., 2008a, Mooney et al., 2013a, Gathercole et al., 2015b, Claudino et al., 2017). The CMJ test provides a reflection of changes in neuromuscular function as a result of training and resultant neuromuscular fatigue (Gathercole et al., 2015d), is practical and simple to perform and importantly places minimal physiological strain on the athlete (Gathercole et al., 2015b). Both single maximal efforts and averaging 3 or 5 jumps are effective for establishing neuromuscular status (Gathercole et al., 2015b, Cormack et al., 2008c), with the decrement in CMJ performance reflective of decreased knee muscle-tendon strength and increased stiffness which increases the ground contact timing (Toumi et al., 2006).

2.6.6 Key physiological structures contributing to CMJ performance

The greatest contributor to the work performed during the maximal jump is the muscular structures acting on the knee joint (49%), followed by the hip (28%) and ankle (23%) joints (Toumi et al., 2006). The initial downwards movement of the CMJ; the eccentric lowering, involves knee and hip flexion and is calculated from force plate data from the time at which the vertical force begins to decrease (Ortega et al., 2010, Linthorne, 2001, Toumi et al., 2006). Knee flexion is controlled by the contracting quadriceps, whilst hip flexion is driven by the hamstring and gluteus maximus muscle groups. At the lowest point of the CMJ, there is a transfer from eccentric to concentric contractions which is known as the amortization phase, when the vertical velocity of the body mass centre changes from a negative to positive (Toumi et al., 2006, Hori et al., 2009). The hips and knees then extend, utilizing the force generated in the eccentric stretching and powering the body off the force plate to perform a maximal jump (Ortega et al., 2010). The eccentric pre-contraction state develops a higher number of attached cross-bridges, which results in the rate of force production (McGuigan et al., 2006). A higher level of muscle activation in the eccentric phase, results in greater elastic energy storage in the muscles and tendons producing a higher takeoff velocity (Linthorne, 2001). A more rigorous initial eccentric phase in the CMJ produces a larger height. Increasing the eccentric speed allows for a greater rate of force production, and thus more work produced in the concentric phase, resulting in increased height and ground reaction forces (Linthorne, 2001, Hori et al., 2009). The increase in series elastic component is driven from the tendon structures, with more prevalent fast-twitch muscle fibres in the knee extensors having the ability to store more elastic energy to be utilised to produce a greater jump performance (Kubo et al., 1999). There is an automatic protective response triggered from the muscle spindles, forcing the quadriceps into rapid leg extension. This causes the involuntary muscle contraction as it is a reactionary response – and results in the stretch reflex. Any interruption to the fundamental compensatory muscle-stabilizing activity due to fatigue or another adverse mechanism may result in less stability of the knee joint, making it unable to resist external forces, and more susceptible to damage of the ligament and surrounding muscles and structures (Rozzi et al., 1999). A decrement in CMJ performance reflects decreased knee muscle-tendon strength and increased stiffness which increases the ground contact timing (Toumi et al., 2006). Lower limb muscle stiffness can result in less pre-stretch extension, and whilst this didn't appear to have a substantial affect on jump height, stiffness is associated with in-effective utilization of elastic energy, and a poorer overall jump performance (Kubo et al., 1999). With no substantial effect on height observed, only a metric that would be able to account for the elastic pre-stretching phase of the jump where energy is generated such as FT:CT, would be sufficient for determining NMF.

2.6.7 Metrics detected from CMJ performance

A number of studies have investigated the validity and reliability of measures detected from a CMJ for detecting neuromuscular status in team sport athletes. Performing the CMJ on a force plate yields a variety of different measures (Table 2.2), however there is uncertainty surrounding which measure is the best indicator of neuromuscular status. Few studies have comprehensively explored the impact of multiple variables for detecting alterations in neuromuscular status (Gathercole et al., 2015c, Cormack et al., 2008c). Perhaps due to the ease in measuring and quantifying, as well as due to equipment limitations, jump height has been the most commonly reported metric from CMJ performance to account for altered movement and neuromuscular status in a variety of team sport athletes (Gathercole et al., 2015b, Buchheit et al., 2017, Malone et al., 2015). Alternative variables that have further been reported from both CMJ and squat jump (SJ) performance include: peak and mean velocity, power, and force, which all relate to the overall final outcome of the jump performance (Taylor et al., 2012a, Russell et al., 2015, Crewther et al., 2009b). Given the CMJ utilizes and reflects the SSC, isolating any jump outcome measures associated with peak force and power and also jump height, doesn't encompass the underlying generating movement the athlete performs, which is an important consideration when accounting for any changes in movement efficiency and strategy (Gathercole et al., 2015b, Gathercole et al., 2015c, Cormack et al., 2008a). Outcome measures further, only detect the final phase of the jump without accounting for the pre-stretch eccentric phase (Gathercole et al., 2015b, Cormack et al., 2008a). In a fatigued state, athletes may be able to maintain an overall jump height, but have actually changed peak angular velocity and power produced in the knee joints to perform the explosive movement of the upward phase of the jump (Gathercole et al., 2015b, Cormack et al., 2008c, Cormack et al., 2008a). This observed change in velocity and power suggest athletes' moderate their performance and muscle activation to counterbalance the loss of force generating capacity when fatigued to still execute a maximal jump, which may maintain jump height (Rodacki et al., 2002, Gathercole et al., 2015b). The ability of the neuromuscular system to reorganize movement structures to still produce force and power and perform a maximal jump movement reflects an altered muscular coordination pattern (Rodacki et al., 2002, Gathercole et al., 2015b). Therefore, athletes may not display a meaningful change in measure of peak power, force or jump height, but there has been a re- organization of the underlying muscular structure (Rodacki et al., 2002, Gathercole et al., 2015b), which likely has implications on performance. A further limitation of recording jump height using a force platform is an overestimation due to landing height being lower than at take-off (Linthorne, 2001). Also, athletes jump height has differed, depending on the calculation from the centre of mass or if it is derived from other measures such as flight time or take-off velocity (Cormack et al., 2008c). Given the importance of the eccentric pre-loading to produce the maximal force for jump height, a measure that has the ability to reflect the potential changes in movement efficiency is more attractive. There has however been a lack of comprehensive analysis identifying what specific measures collected thorough CMJ performance are truly sensitive and reliable within particular cohort of athletes and also to varying level of load exposure. The exploration of the intra- and inter-day reliability of both the typically-derived and alternative CMJ metrics has been identified from single and 5 consecutive jumps in AFL athletes (Cormack et al., 2008c), a 6 bout effort in collegiate level team-sport athletes (Gathercole et al., 2015b), and weekly assessment over a 6-week monitoring period in elite female rugby players (n = 12) (Gathercole et al., 2015a). There was a unanimous low level of validity observed for jump height from a single jump, which was lower for a series of 5 CMJ compared to the single. For the single CMJ, mean and relative mean force displayed the greatest overall reliability (%CV of 1.1% and 1.2% respectively). A number of other variables (peak and relative peak force, peak and relative peak power, mean and relative mean power, and FT:CT) also displayed high reliability (CV <10%) (Cormack et al., 2008c). The Flight time:Contraction time (FT:CT) ratio, collected from force plate technology, provides the relationship between the countermovement phase (eccentric + concentric time) and the resultant flight time (time the athlete is in the air) (Cormack et al., 2008c, Cormack et al., 2008a). See Figure 2.8 for an example of a force trace and highlighting the phases of the CMJ that are used to determine FT:CT. Contraction times is the initiation of the countermovemnt until toe off and flight time represents the time from toe off unti landing. This measure has been identified as more sensitive in reflecting neuromuscular function in elite AFL athletes (Mooney et al., 2013a, Cormack et al., 2008a, Cormack et al., 2008b), and will be explored in further detail below; however, its application with football has not been identified.

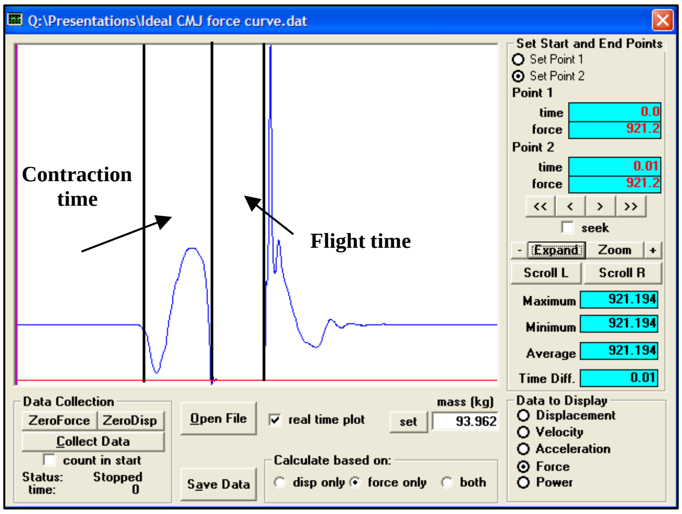

Figure 2.8 Force trace collected from a maximal countermovement jump that shows the phases of the jump used to determine flight time to contraction time ratio (FT:CT)

Changes in the CMJ measures including FT:CT are related to a number of external load parameters to assess the neuromuscular status of athletes in response to preceding load (Cormack et al., 2008c, Gathercole et al., 2015a, Ronglan et al., 2006, Crewther et al., 2009b, Buchheit et al., 2017, Johnston et al., 2016, McLean et al., 2010). In particular, there has been a focus on AFL research with application of the FT:CT to detect neuromuscular fatigue.

A comprehensive analysis of the variables detected from CMJ performance following AFL match play reported limited response when post-measures were compared to pre-match, including that of jump height (Cormack et al., 2008a). However, when compared to 48 hours pre-match, FT:CT did display a substantial reduction for up to 72 hours (-7.5% immediately post and -7.8% at 24 hours post), although data was not collected at 48 hours post-match (Cormack et al., 2008a). There were also substantial reductions mean and relative mean power and relative mean force when comparing to pre-match and 48 hours pre-match (Cormack et al., 2008a).

The exploration into the impact of training load on various CMJ variables has been identified in team sport athletes including AFL, rugby and football. A comprehensive study exploring the change in CMJ variables to increased training load in elite female rugby athletes was conducted using 3 jumps performed on a force platform (Gathercole et al., 2015a). Both manufacturer derived and alternative calculated measures were assessed in response to a 6 week training period, with CMJ performed on a weekly basis (Gathercole et al., 2015a). Further exploration into numerous CMJ variables (22 in total; 16 typical and 6 derived) and their reliability was conducted with collegiate team sport athletes (n = 11), but was limited to only 6 trials (Gathercole et al., 2015b). Therefore, there remains uncertainty about the time-course of neuromuscular fatigue following training and match load in football. In elite male youth footballers (n = 9), there was no substantial change in CMJ performance; determined via jump height in relation to the training load distribution across a training week microcycle (Malone et al., 2015). The limitations of jump height for reflecting NMF have been described prior in this section and data was limited to 9 elite youth footballers, which warrants further investigation. In another football specific study, following match play, peak power and force were substantially reduced immediately post and at 24 hours post-match from both SJ and CMJ performance in the starting team (Hoffman et al., 2003). It was observed in the starting players that a 15.5% reduction in CMJ peak power and a 12.4% reduction in SJ peak power were observed at 24 hours post-match compared to pre-match. There was a reduction in peak force in both the CMJ and SJ performance by 9.4% at 24 hours post match (Hoffman et al., 2003). However, the study did not account for match load variation, solely comparing starters to non-starters. The study was also limited to only reporting on the outcome of power and force measures. Similarly in response to American football match play, both SJ and CMJ performance were reduced across the 4 quarters of a game, suggesting in-match neuromuscular fatigue altering peak power and force of jumping performance. However, when comparing the performance between the two jumps, the CMJ performance was maintained to a greater extent than the SJ, which suggests that the eccentric component of the CMJ may have been less impacted by muscle fatigue and therefore having less of an impact on the neuromuscular factors impacting SSC compared to a quicker concentric fatigue response (Hoffman et al., 2002). Whilst prior studies have provided somewhat useful information and suggested that jump performance is hindered as a result of neuromuscular fatigue from match play, inconsistencies in variables reported, timing of collection, real vs. simulated football activity also the apparatus utilised for measure (jump mat vs. force platform) have resulted in no clear time-course of response or sensitivity of measures (Andersson et al., 2008, Castagna and Castellini, 2013, Krustrup et al., 2010, Clarke et al., 2015, Goodall et al., 2017, Ronglan et al., 2006, Rozzi et al., 1999). Further exploration is thus warranted.

Table 2.2 Countermovement jump metrics.

CMJ metric	Description
Jump Height (m)	Peak height – derived from flight time
Flight time (s)	Time in the air – calculated from the difference between landing and take-off time.
Peak Power (W)	Largest power produced during the concentric phase
Relative peak power (W/kg)	Peak power divided by mass (kg)
Mean Power (W)	Average power generated during the concentric phase
Relative mean power (W/kg)	Mean power generated per body mass
Peak Force (N)	Highest force produced in concentric phase
Relative peak Force (N/kg)	Peak force produced per body mass
Mean Force (N)	Average force generated in concentric phase
Relative mean force (N/kg)	Average force per body mass
Eccentric time (s)	Duration of the eccentric lowering phase – determined from the start of the countermovement to the start of the concentric phase.
Concentric time (s)	Duration of the concentric phase – determined from the end of eccentric phase to toe off.
Flight Time:Contraction Time	Ratio comparing the time the athlete is in the air (flight time) to the combined eccentric + concentric time (contraction time).

2.6.8 Impact of changes in CMJ on subsequent performance

The effectiveness of CMJ performance, and in particular the FT:CT metric for reflecting athletes post-match NMF recovery has been identified in a variety of team sports including AFL, rugby and netball (Cormack et al., 2013, Cormack et al., 2008a, Cormack et al., 2008b, McLean et al., 2010). In football studies however, there has been a reliance on jump height or peak power when accounting for neuromuscular recovery (Silva et al., 2013, Magalhães et al., 2010, Malone et al., 2015, Zemková and Hamar, 2009). The biggest limitation of prior work identifying neuromuscular recovery following match play has been accounting for preceding load on the pattern of response, and individual variance according to playing position. Whilst CMJ has been used as a recovery monitoring tool, there has been limited exploration into the impact of suppressed neuromuscular function determined via CMJ, as a preparatory marker for subsequent match performance. Compromised pre-match neuromuscular status, as result of the distribution of weekly load was identified to impact subsequent match performance in elite Australian Rules football players (Cormack et al., 2013, Cormack et al., 2008a, Cormack et al., 2008b, Cormack et al., 2008c, Mooney et al., 2013a). In response to AFL match play, the FT:CT was identified as the most sensitive measure in detecting the time course of neuromuscular recovery, with a substantial reduction post-match, compared to pre-match as well as 48 hr pre-match. The reduction in FT:CT was also evident at 72 hr post-match, which was considered the crucial time-point and marker for identifying incomplete recovery (Cormack et al., 2008a). Given the sensitivity of FT:CT in response to match play, it was also utilised as the measure reflecting neuromuscular status to identify if incomplete recovery of the neuromuscular system had an impact on subsequent match performance (Mooney et al., 2013a). A reduction in pre-match FT:CT by more than the identified 8% CV, impacted movement efficiency in AFL match play, with a negative relationship between the PlayerLoad™ accumulated per minute (PlayerLoad™.min^{-1}), which was also perceived more negatively by coaches (Mooney et al., 2013a). Suppressed NMF determined by a substantial reduction in FT:CT moderated the ability to produce PlayerLoad™.min^{-1}, as a function of physical capacity (determined from a Yo-YoIR2 test). As a result, a change in an athlete's match activity profile determined via accelerometer derived metrics that reflect a reduced intensity and efficiency to be able to produce the same overall workload output occurs with suppressed NMF (Mooney et al., 2013a).

When the contributions of the individual accelerometer vectors to the overall PlayerLoad™.min^{-1} were assessed in a fatigued state, the most prounounced impact of NMF was a reduction in the contribution of the vertical vector (Cormack et al., 2013). The impact of NMF was identified as resulting in running at lower speeds, with less acceleration, due to the reduction in vertical stiffness and increasing the associated ground reaction forces (Cormack et al., 2013).

Although the concept of NMF impacting movement efficiency is a logical and attractive one, a number of gaps remain. The match activity has previously been averaged across the whole game for different players which hasn't accounted for different levels of match activity exposure. Further, there has been no exploration into the different responses from positional groups and the impact of changes in training and match loading throughout a season, which again may be a confounding factor in the pattern of CMJ performance.

2.7 Football training

Given the dynamic nature of football, training these athletes require not only a stimulus to enhance endurance capacity, in order to perform the total distances required in match play, but also to meet the intensity required for performing the multitude of repeated high-intensity sprint efforts (Hoff and Helgerud, 2004). Along with meeting the volume and intensity demands of match play, football specific training is focused on integrating game specific movements performed with the ball. A large focus on football training is therefore related to technical skill and decision making.

The training for team sports is unique to other endurance based sports in that load is periodized across smaller competition microcycles (Gamble, 2006). An additional challenge to consider with the periodization of training load for football athletes, and in particular with European leagues is multiple matches played during the week. Furthermore, football seasons are long in duration, up to 9 – 10 months, which may only leave a small window of pre-season weeks to develop both the physical capacity foundation as well as refining the tactical and technical skills (Mallo, 2011).

Coaching and conditioning staff generally integrate physical conditioning with tactical and technical elements in their training regime during a competition season with drills involving the ball performed predominantly. Given the demands of teams sports with weekly or multiple weekly matches, alternative periodization models have been utilized instead of the traditional linear periodization evident in endurance based sports (Issurin, 2010). Some examples that have application in football include a block periodization model, where load is concentrated to focus on developing key components of motor ability and skills in isolation over a particular amount of time (weeks for example) (Mallo, 2011), and more recently popularised is a tactical periodization model which has been utilised by influential coach Jose Mourinho at Real Madrid. The appeal of the tactical periodization model is that it promotes a focus of training to be driven from the coaches and key elements of their desired game plan with the physiological demands intertwined and achieved with a football specific focus of movements performed with the ball (Buchheit et al., 2017, Garganta, 2009, Rein and Memmert, 2016, Delgado-

Bordonau and Mendez-Villanueva, 2012, Crespo, 2011). More specifically, tactical periodization breaks down key principles of play, into specific defensive and attacking team set up, with the dynamic actions that occur in between according to playing positions (Delgado-Bordonau and Mendez-Villanueva, 2012).

The training load distribution across the week therefore focuses on these key elements, for example one session may focus on the teams set up when pressing and attacking goal, whilst the next day may target the defensive patterns of play, with the set up and principles associated with defending the opposition. Therefore, tactical, technical, physiological and psychological elements are trained in combination, and whilst days target different components of the demand for football players, they are ultimately related to the tactical set up and football specific exercises (Delgado-Bordonau and Mendez-Villanueva, 2012). Breaking down the overall game plan into independent components is beneficial for skill acquisition and retention of tactical information, due to the repetitive nature of coaching the isolated match elements which repeats each week leading in to match play. With a similar structure of session flow repeated across training weeks, the underlying physical conditioning is integrated with tactical requirement and achieved within these sessions, through the various pattern of play drills. The intensity of sessions are altered to meet the demands of the the specific requirements, with the intensity differing each day to match the variation in training sessions, (see Figure 2.9 below for an example of a tactically periodized week between matches) (Delgado-Bordonau and Mendez-Villanueva, 2012).

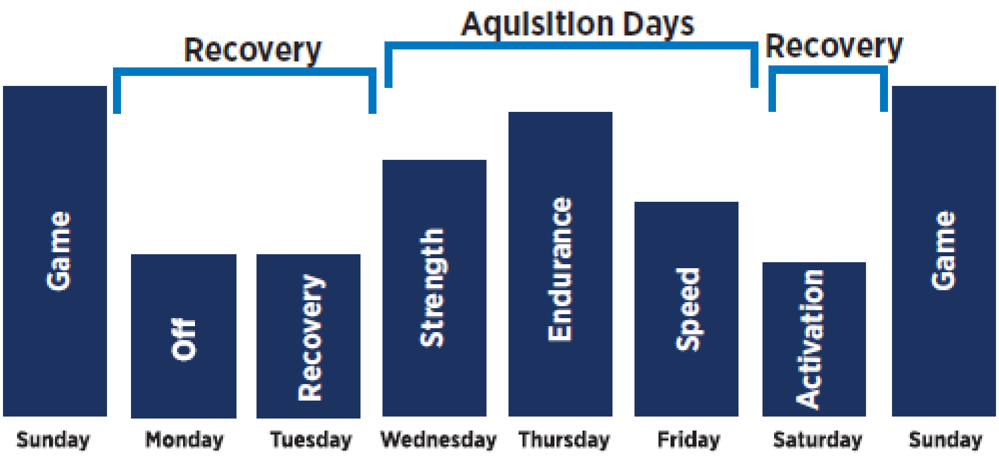

Figure 2.9 Tactical periodization model example. Reproduced from (Delgado-Bordonau and Mendez-Villanueva, 2012).

Given the limited opportunity to expose athletes to training stress in a team sport environment, implementing specific drills that allow for developing combined physiological stimulus, technical and tactical stimulus to meet match requirements is extremely desirable.

2.7.1 Small-sided games

In football training, due to the desire to integrate physiological and technical requirements simultaneously, one of the most commonly implemented and effective drills is the use of a small-sided game (SSG) (Beenham et al., 2017). A SSG approach has gained popularity for inclusion within training cycles to provide an opportunity to effectively perform match specific movements within a confined area (Dellal et al., 2011d, Dellal et al., 2008, Mallo and Navarro, 2008, Hill-Haas et al., 2010, Foster et al., 2010). The use of a SSG also provides a competitive and enjoyable stimulus for athletes. One of the main advantages of the SSG training drill is the control and movement of the ball, whilst experiencing pressures of other players within the confined space (Dellal et al., 2011d, Dellal et al., 2011c, Dellal et al., 2011a). Increased time in contact with the ball, improves decision making and therefore the technical and tactical skills of football players (Sampaio et al., 2009).

The use of SSG drills have also provided an effective conditioning stimulus to promote match specific movement patterns including accelerating and decelerating when changing direction, high-intensity running; when SSG are performed over larger playing areas, sprint efforts, duels and tackles (Köklü and Alemdaroğlu, 2016, Fanchini et al., 2011, Dellal et al., 2011d, Stephen V. Hill-Haas et al., 2009, Jones and Drust, 2007, Iaia et al., 2009, Kelly and Drust, 2009). By manipulating the number of players, playing dimensions, rules (including restricting touches and adding recovery runs), promoting coach encouragement and including goal keepers allows for different physiological and perceptual responses to be achieved in SSGs (Rampinini et al., 2007b, Fanchini et al., 2011, Köklü et al., 2011, Dellal et al., 2011b, Abrantes et al., 2012, Aslan, 2013, Dellal et al., 2011c, Hill-Haas et al., 2010, Casamichana and Castellano, 2010, Halouani et al., 2014, Mallo and Navarro, 2008, Köklü et al., 2015, Hill-Haas et al., 2011).

Different styles of SSG may include “interval” sets (for example 4 sets of 4 minutes) or a continuous set (for example 1 set of 24 minute) (Hill-Haas et al., 2009). Both SSG styles have their merits, with interval allowing for shorter bursts of explosive work, given the duration restriction, whilst the continuous style can promote more tactical performance. The longer duration SSG is also commonly met with a larger playing area, which can provide a greater opportunity for open space movement and high-speed running. The interval style SSG has been shown to illicit the same response of intensity to traditional interval running training (4 x 4 minutes at 90-95% max HR), in junior football players (Impellizzeri et al., 2006). The identified parallel between the intensity of performing a SSG similar to that experienced during traditional aerobic running drills has provided support of the SSG as an appropriate conditioning drill to improve fitness, at the same time as exposing the athletes to specific football movement, which may be preferable over just isolated running. Whilst it appears that the SSG may promote an intensity similar to that experienced in football match play, when specifically comparing the work performed in SSG to friendly match play in semi-professional football players (n = 27), there were differences identified (Casamichana et al., 2012). Whilst the intensity performed in SSG, (determined by work:rest ratio, total PlayerLoad™ and exertion index) was higher than what was performed in a friendly match, given the restraints on the size of the pitch, the researchers did not provide a sufficient stimulus to replicate the high-intensity running (5.83 $m.s^{-1}$) and sprint efforts achieved throughout match play (Casamichana et al., 2012). This is a consideration of the manipulation of playing area.

Further, in elite male junior basketball players (n = 11), whilst the peak HR was similar between a SSG and match play, the global measure of PlayerLoad™, mean HR, and predicted aerobic ($\dot{V}O_{2max}$) demands were lower in a SSG compared to match play (Montgomery et al., 2010). However, whilst overall PlayerLoad™ was identified in this study with basketball players, it is not yet clear how specific multi-directional accelerometer derived movements change in a SSG drill in response to training load and further the impact of SSG movement efficiency on subsequent match intensity.

There was no substantial difference in the overall distance covered, distances relative to walking, jogging and moderate running (0 – 4.97 $m.s^{-1}$), or blood lactate $[La^-]_b$ response in interval SSG (4 x 6 minute efforts) versus continuous (1 x 24 minutes) in youth football players (n = 16) (Hill-Haas et al., 2009). The interval SSG did produce greater high-speed running (>5 $m.s^{-1}$) and a higher sprint:work ratio compared to the continuous SSG (Hill-Haas et al., 2009). It was thus concluded that a interval SSG provides an effective stimulus for developing high-intensity running and repeat sprint efforts (Hill-Haas et al., 2009). A higher RPE resulted from shorter duration SSG (example; 2 sets of 3 minutes) compared to longer durations (for example 4 x 6 minute bouts) (Hill-Haas et al., 2009). Increasing the pitch size and player numbers has elicited a higher intensity in SSG drills; as reflected by increased HR, RPE and $[La^-]_b$ (Hill-Haas et al., 2011).

Manipulating the number of players in SSG drives differences in intensity and physiological responses (Hill-Haas et al., 2009, Hill-Haas et al., 2010). Alternative SSG includes even playing teams of: 3 v 3, 4 v 4, 5 v 5, 6 v 6, odd numbers to provide an overload (e.g., 6 v 5) or the use of a “floating player” (an extra player who doubles and plays for the team that is in possession at the time they receive the ball (Hill-Haas et al., 2010). For example, HR and RPE responses were increased during SSG with fewer players when comparing: 2 v 2, 3 v 3, 4 v 4, 5 v 5, 6 v 6 and 8 v 8 in English Division 1 professional football players (n = 28), due to more direct involvement in a free-play style (Little and Williams, 2007). Comparing differences in playing numbers, specifically 4 v 4 to 8 v 8 SSG resulted in no substantial difference in total distance, and measures of walking, jogging and sprinting but athletes performed a greater amount of backwards and sideways movements in the 4 v 4 style (Jones and Drust, 2007). The 4 v 4 also increased player’s number of ball contacts providing a greater exposure to perform technical skills compared to the 8 v 8 (Jones and Drust, 2007). The study by Jones and Drust comparing the activity profile of 4 v 4 to 8 v 8 SSG was limited though by the quantification of activity profile via video camera and hand notational approach, with distances estimated based on stride length (Jones and Drust, 2007). An 8 v 8 SSG has also produced a lower HR and RPE compared to a 6 v 6 SSG, adding support to greater intensity with reduced players. Given the 8 v 8 is often performed with players in tactical positional formation this dictates movement and activity profile compared to a 6 v 6 which is generally a free-play SSG style (Little and Williams, 2007). Perhaps as a result of greater involvement and ball contacts in a 4 v 4 SSG, a higher mean HR response was observed compared to a 6 v 6 SSG in elite junior Rugby League players which was comparable to a HR appropriate for aerobic conditioning (Foster et al., 2010), and also demonstrating increased intensity with fewer numbers. When comparing a 3 v 3 to 4 v 4 SSG in basketball players whilst both SSG were performed above 80% of HR max, an increased CMJ performance was identified following 4 v 4 compared to pre, which was suggestive that the 3 v 3 with one less player was performed to a greater intensity (Sampaio et al., 2009). But CMJ assessment was accounted for via flight time and jump height, from only 8 athletes limiting the true interpretation of the 3 v 3 game style being performed to a higher intensity (Sampaio et al., 2009).

Whilst it is difficult to compare the SSG findings across different sports as the specific sport demands differ, factors including game area, players and duration all influence the physiological impact that SSG has (Sampaio et al., 2009). An increased RPE has been observed in SSG with less playing numbers due to the greater requirement to be involved in ball movement. However, the intermittent SSG style, which allows for a rest period between sets, has produced a lower RPE than a continuous SSG set (Hill-Haas et al., 2009). Prior research and data presented provides, in essence, a rationale for the effectiveness of SSG utilization as a style of drill that produces a response similar to that required to produce aerobic conditioning, and may provide an appropriate drill for changes in movement pattern under a fatigued state.

Whilst several studies have quantified changes in intensity and work output from SSG drills and compared the response of different playing numbers and field dimensions, limited work has identified changes in technical performance in these drills (Casamichana et al., 2014). Limiting the touches per player (for example to 2) has resulted in differences in activity profile compared to a un-limited free-play style of SSG (Casamichana et al., 2014). A substantial reduction in total distance, distance covered at a speed $\geq$1.9 $m \cdot s^{-2}$, PlayerLoad™.min, work-to-rest ratio and maximal speed was identified in the second 6 minute set of a free-play SSG compared to the first set, whilst no difference across sets was observed in comparison with a limited 2 – touch style SSG (Casamichana et al., 2014). Restricting a team to two-touches per player however revealed no substantial change in movement patterns between the two sets of 6 minutes of 6v6, in semi-professional male footballers (n = 12) (Casamichana et al., 2014). It appears that possession style, as opposed to shooting for goal, increases measures of physical demands in semi-professional football players (n = 14) (Castellano et al., 2013).

The duration of SSG bouts affects the internal and external load parameters of heart rate, $[La^-]_b$ and high-speed movement (Köklü et al., 2017). A reduction in number of players in SSG increases the contact and movement with the ball due to a greater involvement leading to a increased workload, whilst increasing the duration in contrast, reduces the workload (Castellano et al., 2013). Manipulating SSG duration leads to an alteration in movement intensity, especially with the longer bouts which may be the result of fatigue, a reflection of athlete pacing strategy, or due to stopping the game to provide tactical or structural feedback (Fanchini et al., 2011, Casamichana et al., 2014). Increasing the SSG duration from 2 minutes to 6 minutes, resulted in slight change in exercise intensity (determined by average HR), but having no effect on players technical actions (Fanchini et al., 2011). This provides support that athletes have the ability to manipulate their movement pattern, with some change observed in their intensity, to still achieve the same outcome. This may be a reflection of compromised neuromuscular status; however, no study has investigated this concept to-date. Further, to account for movement intensity and efficiency in SSG, previous work has focused on the athletes HR response, velocity metrics including overall distance and distances covered at varying speeds (Mallo and Navarro, 2008, Hill-Haas et al., 2010, Dellal et al., 2011b). For determining the physiological response to SSG drills, measures of HR, $[La^-]_b$ and RPE have been utilised (Köklü et al., 2011, Rampinini et al., 2007b, Stephen V. Hill-Haas. et al., 2009). Whilst the aforementioned global workload measures including HR, RPE and velocity associated distance and speed metrics provide a good global indicator of exercise intensity, they lack the ability to detect multi-plane movements performed to provide a better indicator of movement efficiency. The impact of various accelerometer derived metrics which have the ability to detect alterations in the movement patterns performed in multiple directions is yet to be explored in SSG.

Further, whilst there has been a number of studies that have explored the SSG performed with youth football athletes (Stephen Hill-Haas et al., 2008a, Stephen Hill-Haas et al., 2008b, Hill-Haas et al., 2009, Stephen V. Hill-Haas et al., 2009, Stephen V. Hill-Haas. et al., 2009, Hill-Haas et al., 2010, Dellal et al., 2011c, Köklü et al., 2011), seemingly more limited exploration has been performed with elite footballers and their pattern of movement during SSG drills (Dellal et al., 2011b, Kelly and Drust, 2009).

Of the previous work conducted, the benefit of SSG as a training drill has been extremely useful, yielding different work output depending upon the manipulation of elements including number of players and pitch size. A reduced amount of players, for example 2 v 2, 3 v 3 or 4 v 4 promote a more fast-paced fluid playing pattern, with associated increased involvement of players and the ball. Players have to therefore perform both attacking (passing and dribbling to create a shot at goal) and defending (tackling and providing pressure on opposing players to prevent a goal) roles, therefore increasing backwards and sideways movements (Dellal et al., 2011c). Whilst a larger style for example 8 v 8 or 9 v 9 may be utilised for a more tactical driven game, replicating position specific movements and therefore reducing the intensity, it provides more of a chance for maximal high-speed running (Jones and Drust, 2007). Overall the attractiveness of the SSG is that they produce a workload intensity parallel to traditional aerobic running drills, useful for conditioning and coupled with promoting skill based technical and tactical movement (Dellal et al., 2011c). It is unclear however, how a compromised neuromuscular status may impact a standardised drill such as a SSG. It has been described previously in this literature review that compromised neuromuscular status pre-match (based on a reduced FT:CT) led to a reduced contribution of the vertical accelerometer vector to overall PlayerLoad™.min^{-1}, which was associated with a modification to vertical stiffness (Cormack et al., 2013). This was considered the outcome of increased lower speed running, which leads to altering the vertical stiffness via less vertical acceleration, increased vertical displacement and ground contact time (Cormack et al., 2013, Girard et al., 2011). This important finding was only able to be identified using accelerometer metrics that can discriminate between individual movements performed in multi-plane directions.

The usage of a standardised SSG drill may go beyond a simple reflection of match intensity and exposure to technical skills. When considering the periodization of load across the training week, SSG are generally performed in the same order in the session and at the same time of week. Given the parallels demonstrated with the movements performed and intensity of SSG replicating match play, and also the impact of neuromuscular status in altering match movement efficiency, whilst speculative a novel concept that requires further exploration is that detecting alterations in SSG movement patterns may be responsive to increased load and impact subsequent match performance. It would appear plausible, given the limitations of HR response to adequately reflect intermittent high-intensity exercise, that alternate measures associated with ground contact and running movements, such as accelerometer derived metrics, may provide useful information.

Given that SSG can be used to replicate match activity, there is therefore the potential that they may be useful for determining changes in activity profile that may have similar implications during match play. Utilising a common training drill such as the SSG may provide extremely beneficial information for determining changes in match physical activities based on a football exercise-mode specific field test (Castagna et al., 2010). Different field specific tests have been proposed as alternatives to traditional shuttle-running tests for endurance assessment. There has previously been limited association identified between a field test that contains sport-specific movements such as dribbling; Hoff test and the physical attributes of match performance such as total distance, high-intensity activities and running, and sprinting (Castagna et al., 2010). However, this investigation was limited to exploring the relationship to velocity based metrics, and it is not known how the activity profile of a standardised training drill such as a SSG relative to match activity profile under fatiguing conditions.

2.8 Determining a true change in an athlete's performance

On a comprehensive and sophisticated level, understanding the changes in an athlete's performance with the integration of numerous factors acting as independent variables impacting the dependent variable requires detailed mathematical modelling. On a more simplified level, a substantial change in performance can also be determined in relation to athletes smallest worthwhile change or minimal clinically important difference (MCID) (Thorpe et al., 2017). Calculating the MCID involves the standard error of measurement (typical error; TE), or as an alternate, the between subject SD (for example: >0.2 SDs) via reliability analysis (Thorpe et al., 2017, Hopkins, 2000). A substantially important change in measurement can be deemed by greater than 2 times the standard deviation of difference (multiplying the TE by the square root of 2) (Thorpe et al., 2017, Hopkins, 2000). When identifying a change in athletes' performance, it is important therefore that changes are considered outside of the normal variability expected for the individual athlete for the particular measure of performance. To identify a change in an athlete's performance requires quantification of the particular test measure being collected and knowledge of whether it is valid and reliable for analysis. This is an important consideration, and must be identified prior to identifying a change in an individual's response (Drust et al., 2007, Hopkins et al., 1999). For a test to be considered effective, it must display specificity to what is aiming to be identified, a high level of validity and reliability to determine a true change and also the consideration of whetherathletes are following their usual training and dietary practices during the time when the test is performed and data collected (Hopkins et al., 1999). Further, in a team sport environment, quantifying within- and between-player variation in performance, allows for a reference point and the establishment of the smallest worthwhile change in outcome measures, which allows for the quantification of changes not only between matches or training sessions, but also for the individual athlete (Hopkins, 2004b, Batterham and Hopkins, 2006, McLaren et al., 2016). Within a team sport environment, the response by individual athletes may be vastly different, which therefore supports the use of quantifying individual differences and detection of the smallest meaningful change of a valid and reliable measure of performance.

One of the most commonly used assessments that has received application in team sport for identifying changes in performance is via the magnitude based inference (MBI) approach (Batterham and Hopkins, 2006, van Schaik and Weston, 2016, Hopkins, 2007, Hopkins et al., 2009). A positive effect is interpreted above that considered to be the smallest important positive effect, whilst a negative effect, is the opposite and falls below that defined to the smallest important positive effect, whilst any trivial effects cross-over between the thresholds set for both positive and negative effects (van Schaik and Weston, 2016).

2.9 Overall summary of the current football research on load, recovery and performance

Association football is the most popularised sport around the world. Given footballs popularity, a plethora of research has evolved quantifying the workload performed by a football player during match play and training from various competitions, playing levels, genders, and under differing conditions such as heat and altitude. There has also, to a lower extent been an exploration into a football player's response to training and competition load under a range of differing conditions and also from differing competitions, age levels and genders.

The training process in team sport is designed with the goal of preparing athletes for match intensity and simultaneously protecting from load related injury and illness. Some of the most important factors to consider in the training process are the implications of fatigue and monitoring the fatigue response of the athletes. This has been explored using various markers including RPE, hormonal analysis and NMF monitoring. The pattern of response to training and competition load though, has not been clearly established. Further, whilst markers of the response to training and competition load have been explored in a variety of team sport, there has been minimal consideration for the actual impact of prior training and competition load on the associated changes in response. Acknowledging this gap in the literature, and the desire to explore factors with a direct impact to football, this thesis aimed to, on a global level explore the interaction between training and competition load on recovery and match performance.

Different metrics are available for quantifying both external and internal load in team sport. Whilst external load; the quantifiable volume and intensity performed during a training session or match play, has traditionally been assessed using velocity-based metrics associated with distance and speed (Aughey, 2011), these metrics substantially underestimate total movement by the inability to detect changes in direction, GRF and body contacts. The use of accelerometer derived metrics have the ability to quantify global movement, as well as the potential to distinguish between changes in movement intensity and efficiency via individualised movement vectors (Cormack et al., 2013, Barrett et al., 2016a). Utilization of accelerometer derived metrics has however been limited in football.

Prior research exploring the impact of training and competition load on recovery and fatigue in football, has identified varying time-courses due to inconsistencies in measures, timing of collection with a key factor of the impact of prior load excluded. Of particular interest is the impact of NMF and hormonal response to training and match load, and whilst a thorough identification of the sensitivity of these metrics to match play has been identified in other team sports, such as AFL (Cormack et al., 2008a, Cormack et al., 2008b), there has been no clear identification in football.

Training prescription is challenged in football, due to the demand of one or two matches per week. Therefore, the use of training drills that integrate technical and tactical elements of match play with the overall physiological requirements is common practice. Whilst standardised recovery tests – such as HRR have been utilised with footballers to provide an indication of recovery from prior training and match load, it remains unknown if a standardised training drill can be utilised to reflect changes in activity profile synonymous with fatigue. Given these identified gaps in the current literature, the following studies were designed with the goal of providing some insight.

Study 1 aim: To determine the sensitivity of markers of neuromuscular and hormonal response to various match load. The main objectives to be answered in this study are: What is the most sensitive CMJ measure to display a dose-response relationship to levels of accelerometer derived football match load? What is the time-course of neuromuscular recovery and hormonal response to differing levels of accelerometer derived football match load?

When is the appropriate timing to re-introduce training stimulus following elite football match play?

Study 2 aim: To establish the impact of training and competition load on pre-match neuromuscular recovery, hormonal response and the impact on subsequent match performance. The main objectives if this study is to answer:

What impact does load exposure across various acute and chronic windows have on football match performance?

What impact does load exposure across various acute and chronic windows have on pre-match neuromuscular recovery?

How does a change in weekly neuromuscular recovery and hormonal response impact subsequent match performance?

Study 3 aim: To identoify the impact of training and competition load on neuromuscular recovery and a standardised training drill. The specific study objectives were to answer:

How does a change in weekly training and competition volume impact weekly neuromuscular recovery?

How does a change in weekly training and competition volume impact a standardised SSG training drill?

Can a standardised SSG training drill be used to identify changes in match activity profile in the same way as changes in neuromuscular recovery?

CHAPTER 3. IDENTIFICATION OF SENSITIVE MEASURES OF RECOVERY FOLLOWING EXTERNAL LOAD FROM FOOTBALL MATCH PLAY

3.1 Introduction

Monitoring the external load performed by an athlete and the response to that load is critical to determine when to apply the next training stimulus (Halson, 2014). Velocity and distance metrics are commonly reported measures of external load, yet they may underestimate the load in sports such as football where frequent changes of velocity and direction occur (Coutts and Duffield, 2010, Barron et al., 2014). Tri-axial accelerometers are used to measure global exercise load (Boyd et al., 2011, Mooney et al., 2013a). PlayerLoad™, representing the instantaneous rate of change of the medio-lateral, anterior-posterior, and vertical accelerometer vectors is a valid and reliable measure of external load in team sports (Boyd et al., 2011). PlayerLoad™ discriminates between levels of performance and is modified due to fatigue (Boyd et al., 2011, Mooney et al., 2013a). Accordingly, PlayerLoad™ thus may provide a more complete measure of football load than traditional distance and velocity metrics.

A commonly quantified response to external load is neuromuscular fatigue, which causes impairment of performance through movement modifications, which can have implications for performing skills and also the potential to expose the athlete to a greater injury risk (Cormack et al., 2008a, Gathercole et al., 2015b, Gathercole et al., 2015a). Although gold standard assessment of neuromuscular fatigue requires magnetic or electrical nerve stimulation, this approach is impractical in the applied sport setting (Tofari et al., 2015). To overcome this limitation, neuromuscular fatigue can be quantified via countermovement jump performance (CMJ) (Cormack et al., 2008a, Gathercole et al., 2015b, Gathercole et al., 2015a). Of the variables measured via CMJ, some display high ecological validity as they respond negatively to Australian Rules football match play, and also impact subsequent match exercise intensity (Cormack et al., 2008a, Cormack et al., 2008c, Cormack et al., 2013). The NMF response to football match play has generally been measured via jump height (Gathercole et al., 2015b, Andersson et al., 2008, Silva et al., 2013). The flight time:contraction time (FT:CT) ratio, may provide a more precise quantification of neuromuscular fatigue in team sport athletes than jump height as it may be able to discern changes in movement strategy (Gathercole et al., 2015b). Accordingly, the sole measurement of jump height may underestimate the magnitude of neuromuscular fatigue (Cormack et al., 2008a, Gathercole et al., 2015a, Cormack et al., 2008b). Importantly, altered CMJ performance should be sensitive to preceding exercise load if it is a valid measure of fatigue in the sporting context, but this concept has only received limited attention in the literature (Johnston et al., 2015). The hormonal response to match play (testosterone [T] and cortisol [C] concentration in particular) is also commonly reported (Halson, 2014). Testosterone is an anabolic hormone with an important role in promoting protein synthesis whilst cortisol is a catabolic hormone important in metabolism (Silva et al., 2013, Elloumi et al., 2003). The concentration of T and C are often combined as the T:C ratio, which represents the anabolic:catabolic balance (Silva et al., 2013, Elloumi et al., 2003). Australian Rules football match play resulted in an acute increase in C with little impact on T, whilst the T:C ratio was reduced for up to 48 hours post-match, suggestive of a somewhat catabolic state for this relatively short period (Silva et al., 2013). Despite support for the use of both CMJ performance and the hormonal response to assess the impact of football match play, the influence of preceding match load on the magnitude of the post-match response is not well understood. It is hypothesised that playing a full football game will cause a higher accumulation of neuromuscular fatigue, and hinder CMJ performance longer than playing limited match time. It is also hypothesided that increased match exposer will result in a greater stress response and impact hormones cortisol and testosterone to a greater extent than playing 45 minutes or less of a football match. Therefore, the aim of this research was to determine the impact of football match load on CMJ performance, T, C and the T:C ratio.

3.2 Methods

3.2.1 Subjects

Data (expressed as mean ± SD) were collected from 18 elite football players (age 23.3 ± 4.1 y, height; 180.0 ± 10.0 cm and mass; 75.7 ± 4.4 kg) from one Australian A-League club across three consecutive pre-season Football Federation Australia matches. All players who had any involvement in each match were included in this study and data was averaged across the three matches.

3.2.2 Design

A maximal CMJ and saliva sample was collected at 27-h and 1-h pre-match; 0.5-h, 18-h, 42-h, 66-h and 90-h post-match. Athletes were familiarized with CMJ and saliva collection techniques during a 4-week period prior to the first match. The research was approved by the Victoria University Human Research Ethics Committee with informed consent obtained from each participant and the club prior to commencement.

3.2.3 Methodology

Athletes completed a standardized 2-minute dynamic warm-up with 3 practice jumps prior to a maximal CMJ (Cormack et al., 2008a). The CMJ was performed on a portable force plate (400 Series Platform Plate; Fitness Technology, Adelaide, Australia), at the training ground and connected to manufacturer-supplied software (Ballistic

Measurement System; Fitness Technology, Adelaide, Australia). The force plate was calibrated prior to each trial to minimise variance. Participants performed one CMJ for maximum height with a self-selected eccentric phase depth whilst maintaining hands in position on the hips (Cormack et al., 2008a). Jump height (m), peak velocity ($m.s^{-1}$), relative peak and mean power ($W.kg^{-1}$), relative peak force ($N.kg^{-1}$), contraction time (s) and FT:CT ratio were analysed (Cormack et al., 2008c).

Athletes maintained their usual dietician-prescribed diet throughout the testing period and were instructed to ingest only water in the 60 min prior to providing a saliva sample (Cormack et al., 2008a). To account for diurnal variation, collection of T and C samples generally occurred between 0900 and 0930 with the exception of 1-h pre and 0.5-h post-match. Game 1 and 2 1-h pre-match samples were collected between 1245 and 1315 and game 3 between 1420 and 1450. The 0.5-h post-game samples were collected between 1600 and 1630 for games 1 and 2 and between 1730 and 1800 following game 3. Athletes provided 2 mL of unstimulated passive drool directly into a plastic tube (Cormack et al., 2008a). Samples were frozen at -80^{o}C for later analysis. Duplicate enzyme-linked immunosorbent assay (Salimetrics, PA, USA) using a microplate reader (SpectraMax 190, Molecular Devices, CA, USA) determined C [$\mu g.dL^{-1}$] and T [$pg.mL^{-1}$] concentration (Cormack et al., 2008a).

Accelerometer (100 Hz) derived PlayerLoad™ expressed in arbitrary units (au) accounted for match load. Match load was parsed in to three levels: low-load (0-499 au), medium-load (500-1000 au) and high-load (>1000 au). Although the accelerometer based metric PlayerLoad™ is a continuous variable, that is similar to distance or speed increases over time, the decision to categorise this metric was to account for different levels of global movement. The selection of the 3 levels was based on scatter plot distribution of individual players PlayerLoad™ across the 3 matches was plotted. The points of -27h pre-match and -1h pre-match are reflected by the low PlayerLoad™ only given there has been no exposure yet to match play and therefore all players are at 0. The distribution of PlayerLoad™ from subsequent training relative to low-, medium- and high-loads from the match is displayed in Figure 3.1. The players who had less than 45 minutes of match time and therefore formed the low-load group trained at 18-h post match following data collection after games 1 and 2 as a “top-up” session to account for the limited match time. The training schedule following the matches was:

Match 1 – 18hr post: “top-up” field session for players who had <45 minutes of match time, 42h and 66h post-match: all team field training, 90h post-match: all players recovery day.

Match 2 – 18hr post: “top-up” field session for players who had <45 minutes of match time, 42h, 66h and 90h-post match: all team field training. Of note was that the training session at 90h-post game 1 also doubled as -27h pre game 3.

Match 3 - 18hr post: “top-up” field session for players who had <45 minutes of match time, 42-h post: all team field training, 66-h post: all team recovery session and 90-h post: all team field training.

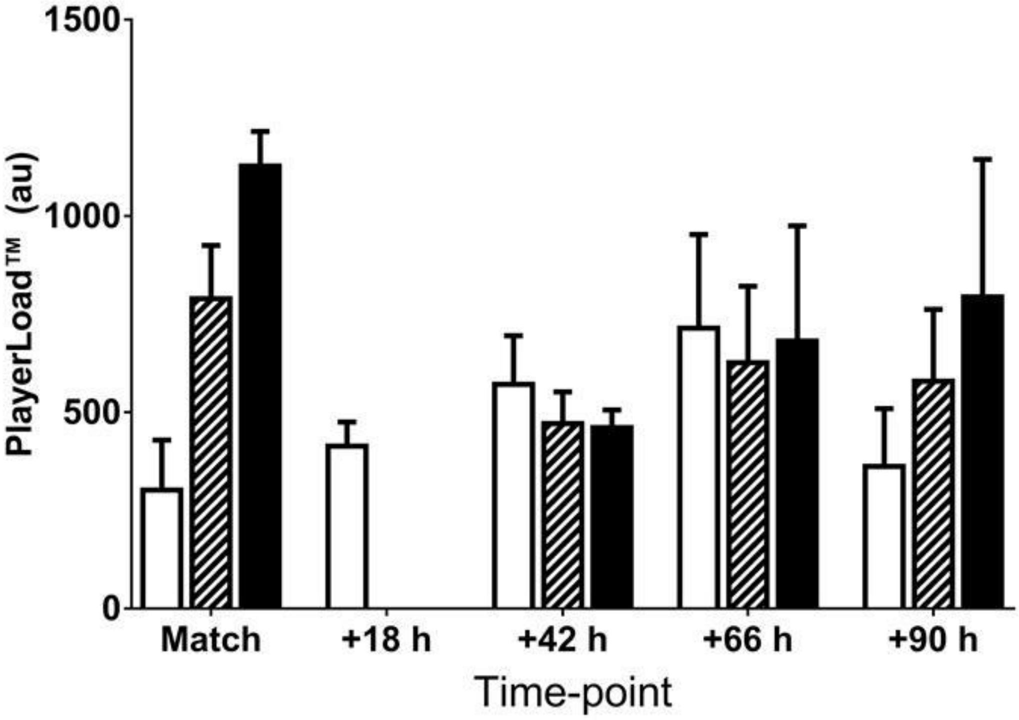

Figure 3.1 Distribution of match and training PlayerLoad™ relative to low-, medium- and high-load groups from match play. Data is presented as group means ±SD. Low-load is depicted in the un-filled columns, medium-load in the hatched columns and high-load in the solid columns.

3.2.4 Statistical Analysis

Separate analyses were performed for each of the measures derived from the countermovement jump and the saliva samples. Each analysis was performed with the same mixed model using the general linear mixed-model procedure (Proc Mixed) in the Statistical Analysis System (version 9.4, SAS Institute, Cary NC). The fixed effects in the model estimated means for each time point, each game and each of the three levels of match-load.

Athlete identity and its interaction with match identity were included as random effects to account for repeated measurement on athletes' within- and between-matches, while a different residual error was specified for each of the seven time points to allow for individual differences in the response to the match load. The smallest residual error was observed at the 90-h post match time point and therefore this was used for the "baseline" reference point to determine a true change in performance that wouldn't be influenced by a higher error and variance.

All measures were log-transformed before analysis then back-transformed to express the changes in percent units, given the log transformation of raw data, a log scale was used when presenting results. To compare the sensitivity of the measures to the effects of match-load, the changes were expressed as t-statistics, which represent a signal-to-noise ratio. The t-statistics were provided directly by the mixed-model procedure. The changes were also expressed in standardized units for assessment of magnitude. Standardization was performed by dividing the change score of the log-transformed measure by the between-subject standard deviation derived from the random effects for athlete identity and its interaction with match identity; this between-subject standard deviation represents the differences between athletes at any given time point free of residual (measurement) error. Uncertainty in the changes was expressed as 90% confidence intervals and interpreted via the non-clinical magnitude-based inference approach (Batterham and Hopkins, 2006). Standardized changes (ES) of 0.20, 0.60, 1.20, 2.0, and 4.0 were thresholds for small, moderate, large, very large and extremely large effects respectively. When the confidence interval for a change included small positive and negative effects, the change was deemed unclear. For clear effects, the likelihood that the true effect was substantial was indicated with the following scale: possibly (25% to 75%), likely (75 to <95%), very likely (95 to 99.5%) and most likely (>99.5%). Data is presented as the % change in mean ± standard deviation (SD).

3.3 Results

3.3.1 Selecting the most sensitive countermovement jump measure

Although there was variability relative to match-load and time-points, jump height, FT:CT and peak velocity displayed the largest ES and t-statistic values (ranges of: 0.2

to 3.0, 0.4 to 3.9 and 0.0 to 3.0 respectively) compared to baseline (90-h post). Peak velocity and jump height displayed the same pattern of response; however the standardised effects for jump height were nearly twice that of peak velocity. As jump height is a commonly reported measure of CMJ performance; it was selected ahead of peak velocity as the variable for further analysis.

3.3.2 Magnitude of change compared to baseline

Mean jump height and FT:CT response to match load are displayed in Figure 3.2 and Figure 3.3 with the change in mean from baseline displayed in Table 3.1. When comparing the jump height between the different levels of PlayerLoad™, at 0.5-h and 18-h post there was a *likely* reduction (10%, ±7%; moderate effect and 7%, ±4%; small effect) in jump height for medium-load. High-load displayed a *very likely* (large and moderate effects) reduction in jump height (16%, ±8%; large effect and 9%, ±5%; moderate effect) at 0.5-h and 18-h post respectively. At 42-h, the change in jump height was *unclear* across all levels of load. Comparing the FT:CT response between levels of PlayerLoad™ identified high-load had a *very likely* 12%, ±7% reduction (moderate effect) in FT:CT at 0.5-h post. At 18-h, there was a *most likely* and *likely* reduction (moderate effects) in FT:CT in medium- and high-load respectively.

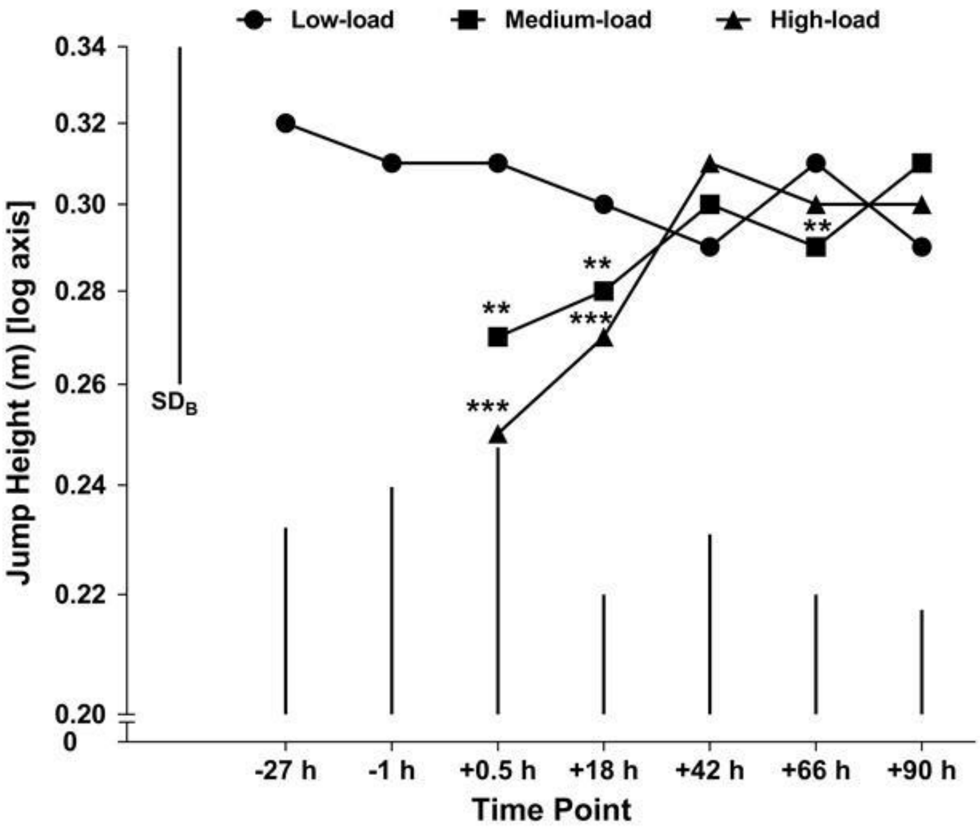

Figure 3.2 Mean Jump height from 27h pre to 90h post of low, medium and high match loads. Mean values are displayed in log scale with the overall between subject SD shown by the bar labelled SD$_B$. The single bars underneath each time-point represent the within subject SD specific to that time-point. Changes exceeding the ES (0.2) with the qualitative descriptor of **likely (75 to <95%), ***very likely (95 to 99.5%) and ****most likely (>99.5%) is displayed. m: meters.

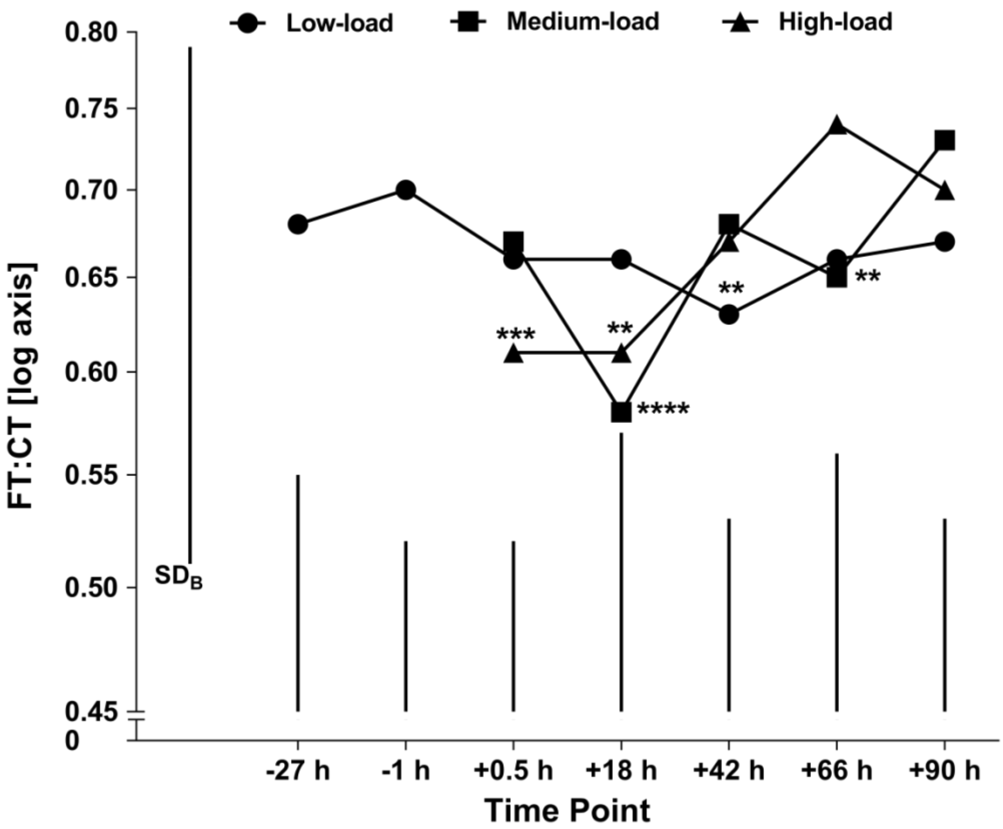

Figure 3.3 Mean FT:CT from 27h pre to 90h post of low, medium and high match loads. Mean values are displayed in log scale with the overall between subject SD shown by the bar labelled SD_B. The single bars underneath each time-point represent the within subject SD specific to that time-point. Changes exceeding the ES (0.2) with the qualitative descriptor of **likely (75 to <95%), ***very likely (95 to 99.5%) and ****most likely (>99.5%) is displayed. m: meters.

Table 3.1 The difference in the magnitude of change from baseline Jump Height, Flight Time:Contraction Time (FT:CT) ratio, Cortisol (C), Testosterone (T) and Testosterone:Cortisol (T:C) ratio between levels of match load.

	Match Load	0.5h post	18h post	42h post	66h post
Jump Height	L	2.4, ±9.1	0.6 ±5.2	-2.6 ±5.3	1.4 ±5.8
	M	-9.9, ±7.3; ↓**	-6.6, ±4.4; ↓**	1.0, ±4.8	-4.5, ±4.8; ↓**
	H	-15.8 ±8.1; ↓***	-8.7 ±5.3; ↓***	3.0 ±6.9	-1.4 ±6.5
FT:CT	L	-5.6, ±6.6; ↓*	-5.3, ±9.9	-9.6, ±6.7; ↓**	-7.8, ±9.9; ↓*
	M	-5.0, ±6.5; ↓*	-17.0, ±7.5; ↓****	-3.6, ±6.4; ↓*	-9.2, ±8.5; ↓**
	H	-12.4, ±6.6; ↓***	-12.6, ±10.3; ↓**	-4.6, ±8.6	2.9, ±13.0
Cortisol [$\mu g.dL^{-1}$]	L	54.6, ±54.4; ↑***	-0.0, ±21.6	-5.7, ±19.9	34.7, ±27.0; ↑***
	M	165.4, ±72.7; ↑****	-14.2, ±17.1; ↓*	-30.7, ±13.3; ↓***	-1.0, ±18.0
	H	101.2, ±62.6; ↑****	2.9, ±21.8	-18.0, ±16.9; ↓**	-8.2, ±17.1
Testosterone [$pg.mL^{-1}$]	L	17.0, ±17.8; ↑**	8.3, ±15.2	12.1, ±14.9; ↑**	21.6, ±20.3; ↑**
	M	19.5, ±15.0; ↑***	-10.6, ±11.4; ↓**	-11.5, ±10.7; ↓**	-9.4, ±13.3; ↓*
	H	17.0, ±16.1; ↑**	5.8, ±14.5	0.8, ±13.1	-5.7, ±14.3
T:C ratio	L	-27.2, ±20.6; ↓**	6.1, ±18.0	16.5, ±18.0; ↑**	-12.4, ±13.4; ↓**
	M	-54.4, ±10.0; ↓****	5.1, ±16.4	29.0, ±18.4; ↑***	-7.0, ±13.0
	H	-42.5, ±14.4; ↓****	3.0, ±17.1	23.2, ±18.6; ↑***	4.1, ±14.7

Values are presented as % change in mean, ± 90% CI; direction of response: positive ↑ and negative↓. Symbols denote: *possibly, **likely, ***very likely and ****most likely chance of the true effect exceeding a small (0.2) effect size. m: meters; [μg.dL-1]: micrograms per deciliter; [pg.mL-1]: pictogram per milliliter. L: low match load, M: medium match load, H: high match load.

Mean C, T and T:C response to the match load tertiles are displayed in Figure 3.4, Figure 3.5 and Figure 3.6 respectively, with the change in mean from baseline also displayed in Table 3.1. Compared to baseline (90-h post), at 0.5-h post there was a *very likely* (moderate effect) increase in C in low-load, *most likely* increase in medium-load (very large effect) and *most likely* (large effect) increase in high-load (range: 55% to 165%). At 18-h, the change in C was *unclear* compared to baseline (90-h post). Testosterone displayed *likely* increases in low- and high-load respectively and *very likely* increase in medium-load (range: 17% to 20%; moderate effects) at 0.5-h post. There were varied responses thereafter. Low-load resulted in a *likely* reduction (moderate effect) in T:C with moderate and high-load resulting in *most likely* reductions at 0.5-h post (very large and large effects respectively). There were *unclear* changes in T:C in all load tertiles at 18-h, with small (low-load) and moderate (medium- and high-load) effects of an increased T:C at 42-h.

3.3.1 Magnitude of change from baseline between levels of PlayerLoad™ (AU)

The magnitude of change from baseline between match load tertiles in all variables is presented in Table 3.2. At 0.5-h, there was a *likely* greater reduction (12%, ±11%; moderate effect) in jump height in medium-load and *very likely* greater reduction (18%, ±11%; large effect) in high-load compared to low-load. There was a *likely* (small effect) greater reduction (8%, ±9%) in FT:CT in high-load compared to medium-load at 0.5-h post . Whilst at 18-h, there was a *likely* greater reduction (12.4%, ±11.8%; moderate effect) in FT:CT in medium-load compared to low-load. There was a *very likely* increase (72%, ±77%; moderate effect) in C in medium-load compared to low-load at 0.5-h post. Differences in the T response between load tertiles were variable whilst the differences in T:C were predominantly unclear.

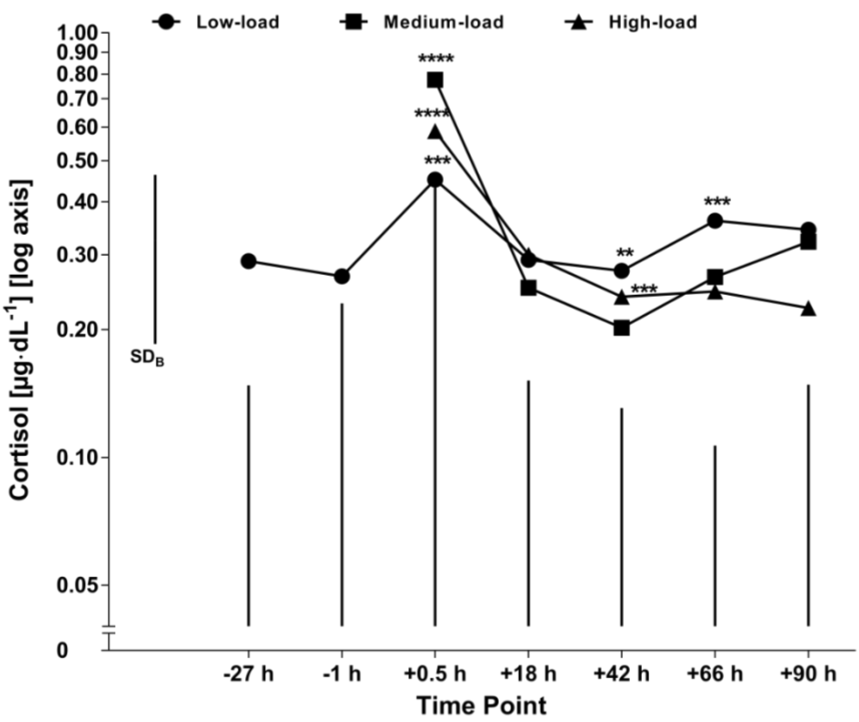

Figure 3.4 Mean cortisol from 27h pre to 90h post of low, medium and high match loads. Mean values are displayed in log scale with the overall between subject SD shown by the bar labelled SD_B. The singular bars underneath each time-point represent the within subject SD specific to that time-point. Changes exceeding the ES (0.2) with the qualitative descriptor of **likely (75 to 95%), ***very likely (95 to 99.5%) and ****most likely (>99.5%) are displayed. [µg.dL^{-1}]: micrograms per decilitre.

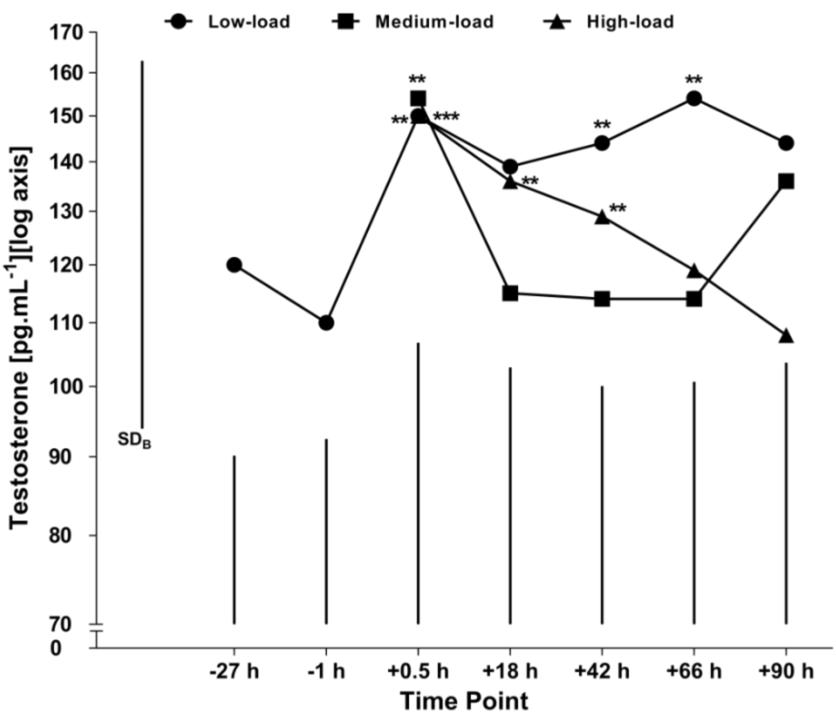

Figure 3.5 Mean Testosterone response from 27h pre to 90h post of low, medium and high match loads. Mean values are displayed in log scale with the overall between subject SD shown by the bar labelled SD_B. The singular bars underneath each time-point represent the within subject SD specific to that time-point. Changes exceeding the ES (0.2) with the qualitative descriptor of **likely (75 to 95%), ***very likely (95 to 99.5%) and ****most likely (>99.5%) are displayed. [pg.mL^{-1}]: pictogram per millilitre.

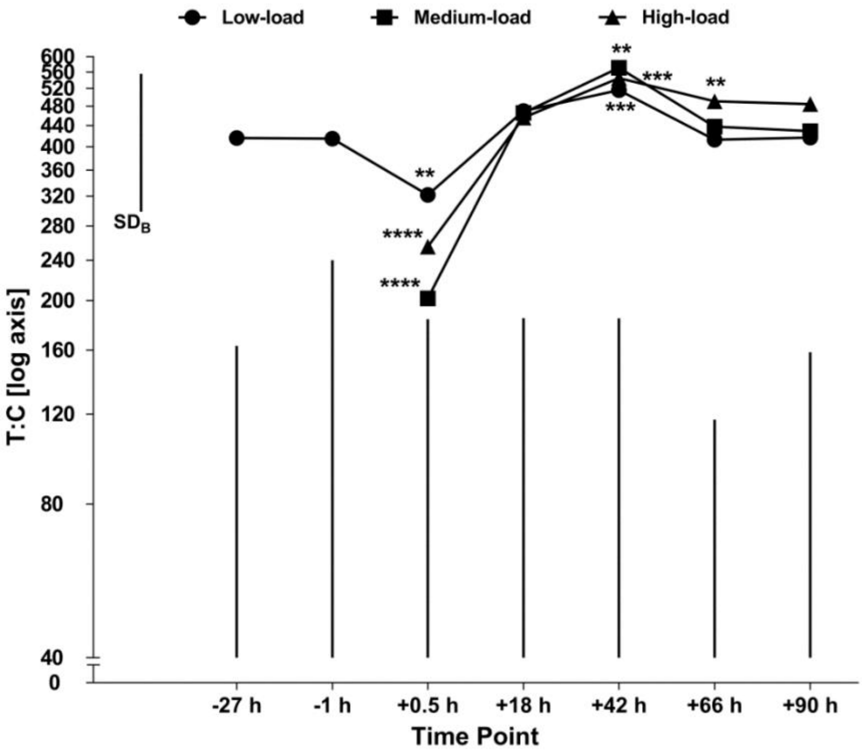

Figure 3.6 Mean T:C response from 27h pre to 90h post of low, medium and high match loads. Mean values are displayed in log scale with the overall between subject SD shown by the bar labelled SD_B. The single bars underneath each time-point represent the within subject SD specific to that time-point. Changes exceeding the ES (0.2) with the qualitative descriptor of likely ** (75 to 95%), very likely * (95 to 99.5%) and most likely **** (>99.5%) are displayed.**

Table 3.2 The difference in magnitude of change between levels of match load on Jump height, Flight Time:Contraction Time (FT:CT), Cortisol (C), Testosterone (T) and Testosterone:Cortisol (T:C).

	Match load	0.5 h Post	18 h post	42 h post	66 h Post
Jump Height	M-L	-12.0%, ±10.7%; ↓**	-7.2%, ±6.7%; ↓**	3.6%, ±7.6%	-5.8%, ±7.1%; ↓**
FT:CT ratio	M-L	0.6%, ±9.3%	-12.4%,±11.8%; ↓**	6.6%,±10.0%; ↑*	-1.6%, ±13.4%
Cortisol [$\mu g.dL^{-1}$]	M-L	71.7%, ±76.6%; ↑***	-14.2%, ±24.6%	-26.4%, ±20.4%; ↓**	-26.5%, ±18.6%; ↓**
Testosterone [$pg.mL^{-1}$]	M-L	2.2%, ±18.5%	-17.4%, ±14.2%; ↓**	-21.0%, ±12.7%; ↓***	-25.5%, ±15.0%; ↓***
T:C	M-L	-37.4%, ±22.4%; ↓***	-0.9%, ±22.2%	10.7%, ±22.5%	6.2%, ±20.5%
Jump Height	H-M	-6.5%, ±11.8%	-2.2%, ±7.2%	2.0%, ±8.4%	3.2%, ±8.5%
FT:CT ratio	H-M	-7.7%, ±8.7%; ↓**	5.3%, ±15.0%	-1.1%, ±10.4%	13.4%, ±17.2%; ↑**
Cortisol [$\mu g.dL^{-1}$]	H-M	-24.2%, ±31.1%	19.9%, ±33.4%	18.3%, ±31.8%	-7.3%, ±21.8%
Testosterone [$pg.mL^{-1}$]	H-M	-2.1%, ±16.1%	18.3%, ±19.8%; ↑**	13.9%, ±17.7%; ↑**	4.1%, ±19.5%
T:C	H-M	26.2%, ±41.3%	-2.0%, ±21.3%	-4.5%, ±18.7%	12.0%, ±20.1%
Jump Height	H-L	-17.8%, ±10.8%; ↓***	-9.3%, ±7.0%; ↓**	5.7%, ±9.1%	-2.8%, ±8.5%
FT:CT ratio	H-L	-7.2%, ±8.7%; ↓*	-7.7%, ±14.0%	5.5%, ±11.4%	11.6%, ±18.0%
Cortisol [$\mu g.dL^{-1}$]	H-L	30.1, ±60.8%	2.9%, ±29.7	-13.0%, ±24.4%	-31.9%, ±17.35%; ↓***
Testosterone [$pg.mL^{-1}$]	H-L	0.0%, ±18.6%	-2.3%, ±17.1%	-10.1, ±14.7%	-22.5%, ±15.9%; ↓***
T:C	H-L	-21.0%, ±29.5%	-2.9%, ±21.8%	5.7%, ±21.3%	18.9%, ±22.9%; ↑**

Values are presented as % change in mean, ±CI; direction of response: positive ↑ and negative↓. Symbols denote: * possibly, ** likely, *** very likely and **** most likely chance of the true effect exceeding a small (0.2) effect size. m: meters; [$\mu g.dL^{-1}$]: micrograms per deciliter; [$pg.mL^{-1}$]: pictogram per milliliter. M-L: medium compared to low match load, H-M: high compared to medium match load, H-L: high compared to low match load.

3.4 Discussion

The aim of this research was to determine the sensitivity of CMJ performance, T, C, and the T:C ratio to load accumulated during football match play. Given the restrictions at the time of the study for tracking devices in regular competition matces, the use of FIFA pre-season friendly matches against teams that would be played in regular competition were utilised to provide the representation of match load. Whilst acknowledging that the intensity of these games may have differed from regular competition match play, the study did identify that elite level football match load altered athletes' subsequent CMJ and hormonal response. Match load mediated the degree of change in jump height and FT:CT, with FT:CT more sensitive to match and subsequent training load. The results of this study highlight the need to consider multiple markers of recovery from match-load.

The magnitude of reduction in jump height at 0.5 and 18-h post-match appears to be modified by match-load. For example, the change was *unclear* at these times in low-load conditions (2.4 ±9.1%), yet *very likely* reduced with large effects when high match loading was experienced (-15.8 ±8.1%). Further, at 0.5-h, when compared to low-load, there was a *likely* (-6.6 ±4.4%) and *very likely* (-8.7 ±5.3%) (moderate and large effects) lower jump height in medium and high-load respectively, with no clear difference between medium- and high-loads evident. Given this finding, it appears plausible that there is a minimum threshold match-load that negatively impacts CMJ height post-match. Similarly, a maximum threshold seems to exist, beyond which, there is limited additional clear impairment of jump performance. As the results indicate a dose-response relationship; this finding provides some support for the ecological validity of jump height as a sensitive measure of an immediate neuromuscular response to football match play. Whilst the mechanisms responsible for the reduction in post-match jump height cannot be determined in this study, there are numerous possibilities (Silva et al., 2013, Fatouros et al., 2010). These include central and peripheral factors including structural changes due to muscle micro-trauma or reduced central drive (Andersson et al., 2008). At 42-h there were unclear changes in jump height, whilst at 66-h there was individual variability in the jump height response to a given match-load. This variability may be a function of the post-match training load, or related to individual athlete characteristics such as lower body strength or fitness impacting athletes tolerance to match loads (Johnston et al., 2015). Similar to the findings shown here, evidence of reduced jump height has been shown to last between 24-h and 72-h, with variation according to level of football competition, timing of testing and match vs. simulated activity (Fatouros et al., 2010, Andersson et al., 2008, de Hoyo et al., 2016).

Despite the support for jump height as a marker of recovery noted above, the results are stronger when considering the use of FT:CT. In contrast to the *unclear* change in jump height at 0.5-h post in low-load, FT:CT was *possibly* reduced in this group and medium-load (although small effects were identified). High-load resulted in a *very likely* (moderate effect) reduced FT:CT at 0.5-h post. Although the impact of a *possible* reduction should not be overstated, this outcome suggests a detection of a change in performance, and thus provides different information about neuromuscular status than jump height alone. Compared to jump height at 18-h post, there was a more likely reduction in FT:CT than jump height; supporting the contention that FT:CT is a more sensitive measure (Cormack et al., 2008a). The likelihood of a reduction in FT:CT was also generally more sensitive than the change in jump height at 42- and 66-h post, particularly in low-load where training occurred immediately after the jump test at 18- and 42-h post match. Thus, FT:CT may be more sensitive to acute load changes than jump height. The observed response may also be representative of the bi-modal pattern of recovery from repetitive stretch-shortening cycle exercise (Cormack et al., 2008a, Rob Gathercole et al., 2015). Regardless of mechanism, this finding adds weight to the concept that impairments to neuromuscular function result in a reorganization of jumping strategy in order to maintain a similar output (e.g. height) (Rob Gathercole et al., 2015, de Hoyo et al., 2016). In such a case, the outcome measure of flight time or jump height is relatively unaffected, but when considered relative to a measure of jump strategy (i.e. contraction time), a decrement may be revealed (de Hoyo et al., 2016, Mooney et al., 2013a, Gathercole et al., 2015b).

In the comparison of the magnitude of change between load groups from 18- to 66-h post, neither jump height nor FT:CT changed with more certainty. It is possible that the arbitrary division of external load used here was too narrow to detect clearly meaningful differences between the match load tertiles. Support for this contention exists in the largely unclear differences in both jump height and FT:CT when comparing medium and high match loads. Beyond the 500 au threshold of low match load, it appears that individual variability (demonstrated by the wide confidence intervals) plays an important role. These individual differences may be related to position, tactics and physical characteristics (Johnston et al., 2015). As PlayerLoad™ represents accelerations in 3 planes it could be that some players have completed relatively more or less low speed activity, high speed running, sprinting, accelerating, decelerating and changes of direction than others to produce the same absolute match load (Bloomfield et al., 2007). It could be that the distribution of activity profile has an impact on the FT:CT response, such that players involved in relatively more intermittent high intensity activities may respond differently than those involved in a higher number of low speed continuous actions. In addition, players within the same match load group could be nearly 500 au apart, which may have impacted the results.

The intensity of football match play resulted in an immediate increase is salivary C across all load tertiles. As with CMJ variables, it is difficult to compare this result to other work, as the activity profile has not generally been accounted for. Intercollegiate male soccer players and rugby league players have had a more than 200% increase in C after match play (Elloumi et al., 2003, Edwards et al., 2006). Whilst in Australian Rules football players, C increased immediately and 24-h post-match by 34% and 42% respectively (Cormack et al., 2008a). Although all load tertiles resulted in increased C post-match, the increases were greater in medium- and high-load compared to low. It appears that elite football match play is of sufficient volume and intensity to cause an increased secretion of C (Elloumi et al., 2003). Unlike the modified CMJ performance, the same dose-response relationship is not evident in C, which appears to be due to substantial individual variation. The reason for this variation is not obvious, however the biochemical response to team sport exercise appears to be influenced by intermittent endurance fitness and similar mechanisms may be at play up until 18-h post (Johnston et al., 2015). In addition, C is influenced by psychological factors that may have played a role in the current results (Elloumi et al., 2003, Hoffman et al., 2002).. By 42-h post, clear reductions in C are evident in the medium and high-load (small and moderate effect respectively), although the difference between these groups is unclear. Finally, the impact of circadian variation on the results due to some inconsistency in sample time collection around matches cannot be ruled out (Edwards et al., 2006, Hoffman et al., 2002).

All load tertiles exhibited meaningful increases in T post-match, with no clear difference in the magnitude of change between tertiles. Variable responses are common, with an average 15% increase post-match in collegiate football, an approximate 20% reduction following rugby match play and no change after elite football match play

(Elloumi et al., 2003, Edwards et al., 2006, Ispirlidis et al., 2008). At 18-h post and beyond, the T response appears to be a function of substantial individual variability. The division of match load into the three broad groups and the potential impact of circadian variation as mentioned previously, may have caused such variability (Edwards et al., 2006, Hoffman et al., 2002). Similar to the contention posed for FT:CT, it may also be that despite a similar external load, players could have achieved this outcome with a markedly different activity profile, impacting individual T responses.

Immediately post-match, there was a *likely* (moderate effect) reduction in T:C in low-low, and a *most likely* reduction in medium-load (very large effect) and high-load (large effect) respectively. The T:C ratio is said to be reflective of anabolic:catabolic balance and the results of the present study suggest an immediate relatively catabolic response to match-play (Elloumi et al., 2003, Cormack et al., 2008a). Similar catabolic states existed following rugby union match play where T:C was 2.5 times lower compared to a rest day, and following 1st division female football match play, where there was a 32% reduction in T:C (Elloumi et al., 2003, Maya et al., 2016). At 18-h post, the change in T:C was uniformly *unclear* (trivial effects). This result appears to contrast previous work in football where T:C was reduced for 48-h compared to pre-match (Silva et al., 2013). However, the uncertainty described here may in fact be a function of the precise statistical analysis employed and more accurately reflect the true individual variability relative to match load (Buchheit, 2016). Interestingly, by 42-h post there were small *likely* (small effect) to *very likely* (moderate effect) increases in T:C suggesting a return to an anabolic environment following the introduction of a training stimulus. It appears that there is a progressive change from a relatively catabolic to anabolic environment somewhere between immediately post-match and 42-h post. Following rugby union match play, T:C changed from an immediate post-match reduction to increased values in the following 4 days (Elloumi et al., 2003). In a similar way to the reductions evident in FT:CT at 66-h post, the clear reduction in T:C in low match load is potentially a function of training load between 42- and 66-h post (Cormack et al., 2008a).

3.5 Conclusions

External load accumulated during elite football match play results in a reduction in CMJ performance and increased C and T concentrations. Reductions in jump height were greatest in players who recorded medium and high match loads at 0.5- and 18-h post match, suggestive of a dose-response relationship. The FT:CT ratio detected an immediate alteration in jump performance associated with higher match loads, and was reflective of altered movement strategy post-match. This study identified wide individual variation, particularly with the hormonal response beyond immediately post match. Therefore, to fully understand the complexities of accounting for individual athlete recovery via neuromuscular and hormonal response to match play within the team environment, sophisticated modelling is needed.

3.6 Practical applications

Football players accumulating a PlayerLoad™ of >500 au have a reduced CMJ performance for at least 42-h. The FT:CT appeared to be sensitive to both match-load and the introduction of subsequent training load typical in a training week. Thus FT:CT is the most useful CMJ variable for assessing recovery post-match. Practitioners should consider assessing this variable from a CMJ at least 42-h post-match to help inform training prescription. The substantial individual variability and cost of analysis of hormonal response raises questions regarding the utility of regular monitoring of salivary hormones in A-League football. Specific changes relative to each individual athlete may be a preferable analysis within the team environment.

CHAPTER 4. LINK BETWEEN STUDY 1 AND 2

It was identified through the initial study that a disturbance to a player's neuromuscular performance and hormonal status lasted for 42h following match play. Importantly, the magnitude of reduction in neuromuscular performance, determined via FT:CT appeared to be impacted by match external load represented by PlayerLoad™. Furthermore, low match load players who undertook additional training also displayed a reduction in FT:CT at a later time-point. These results suggest that FT:CT changes in a dose-response manner to A-League match play or training and that this variable may be useful for the ongoing assessment of neuromuscular fatigue in this population. It was identified that irrespective of PlayerLoad™, both testosterone and cortisol were increased immediately post-match (by 17-20% and 55-165% respectively from baseline). The pattern was less clear in the days following match play, with a reduction in the medium and high load groups, and an increase in the low load group. Similar to the change in FT:CT, the increases seen in the low load group may be a function of additional training. Whilst these results provide insight into the time course of recovery of neuromuscular fatigue and selected hormonal variables after a match, it is unknown whether these responses impact performance in subsequent match play. The usefulness of these measures for ongoing monitoring purposes is somewhat dependant on this. Therefore, the aim of Study 2 was to determine the impact of changes in prior training load assessed across various windows (i.e. 3 – 28 days) on FT:CT, T, C, and T:C and performance relative to playing position.

CHAPTER 5. EFFECTS OF TRAINING AND COMPETITION LOAD ON NEUROMUSCULAR RECOVERY, TESTOSTERONE, CORTISOL AND MATCH PERFORMANCE DURING A SEASON OF PROFESSIONAL FOOTBALL

5.1 Introduction

Maximising performance and minimising injury risk in team sport athletes requires a careful balance of applying training load and recovery (Halson, 2014, Borresen and Lambert, 2009, Jaspers et al., 2016). The application of a training stimulus has both positive (fitness) and negative (fatigue) outcomes (Foster, 1998, Drew and Finch, 2016, Smith, 2003). Performance is thus considered the function of fitness and fatigue. Whilst fitness is relatively slow to develop and decay, fatigue accumulates and dissipates more quickly (Smith, 2003, Williams et al., 2016, Murray et al., 2016). Despite this high level knowledge, very little is known on the specific interactions between training load, the resultant fatigue response and subsequent performance (Aughey et al., 2016).

A common method of assessing internal load in team sports is via collection of the athlete rating of perceived exertion (RPE) (Halson, 2014, Borresen and Lambert, 2008b, Impellizzeri et al., 2004) which is then multiplied by session duration to represent the internal load (session rating of perceived exertion, sRPE) (Scott et al., 2013b, Foster, 1998, Foster et al., 2001). Chronic load (average sRPE over relatively longer periods of training e.g. 4 weeks) has been suggested to represent fitness whilst acute load (sRPE over shorter periods, e.g., 1 week) may represent fatigue (Drew and Finch, 2016). Interestingly, high acute load is suggested to enhance performance

(Sampson et al., 2016). Although training load for a given period is commonly calculated using rolling averages, this does not emphasise the likely greater importance of recent load (Murray et al., 2016, Sampson et al., 2016). Given this limitation, it has been suggested that an exponentially weighted moving average (EWMA) where different decay constants are applied to different length periods should be utilised (Murray et al., 2016, Williams et al., 2017). Regardless of calculation method, it is unclear whether higher or lower training load is positively or negatively associated with football performance and whether this association varies across playing positions.

Whilst the response to match play in different sports has been assessed in various ways including measurement of hormones such as testosterone and cortisol (Cormack et al., 2008a, Cormack et al., 2008b), a recent investigation in elite football failed to show a clear dose-response relationship (chapter 3). However, the impact of changes in the hormonal profile on subsequent match performance was not examined. In contrast, the ratio of flight time to contraction time (FT:CT) obtained from a countermovement jump (CMJ) is a useful indicator of neuromuscular fatigue (NMF) in elite footballers (chapter 3). This CMJ metric yielded a dose-response relationship to match external load in various positional groups (chapter 3). Although this finding supports the efficacy of using FT:CT to assess the post-match response, it is unknown whether pre-existing neuromuscular fatigue measured via FT:CT impacts subsequent match performance in elite football as it does in other sports (Mooney et al., 2013a, Cormack et al., 2013).

In team sport environments, monitoring training and competition load is aimed at maximising performance (Gastin et al., 2013a). However, there is limited understanding of the impact of previous training and competition load on subsequent match performance in elite football players. Furthermore, the influence of NMF, testosterone and cortisol on match performance is also unclear. Given prior research it was hypothesised that a state of NMF or altered hormonal response would cause a hinderance to subsequent match performance. Therefore, the purpose of this study was to examine the interactions between EWMA internal load of different time constants, NMF, hormonal response and match performance (measured via Coaches votes) (Cormack et al., 2013, Mooney et al., 2013a) during a season of elite A-League football.

5.2 Materials and methods

Data for this study were collected from a single elite football team throughout a competitive season that included 34 matches (27 regular A-League, and seven Asian Champions league matches). A total of 23 players (excluding goal keepers) with a mean ± standard deviation (SD) age; 23.3 ± 4.1 yrs, height; 180 ± 10.0 cm and mass 75.7 ± 4.4 kg provided data for analysis. Data was collected from players who were involved in any weekly match time, including substitute players. Given the tactical formation of the team was 4-5-1, players were parsed according to the positional groups of: centre defender, wide defender, centre midfielder, wide midfielder and striker in each game. The Victoria University Human Research Ethics Committee granted approval for this study with written informed consent obtained prior to commencement.

Given the presence of FIFA restrictions at the time of the study for the use of tracking devices during match play, sRPE was used to represent training and match loads. Athletes provided an RPE (0-10) value 30 minutes post-training and match play (Borg et al., 1987), which was then multiplied by the total session duration to provide internal load (Impellizzeri et al., 2004, Foster, 1998).

Cumulative internal load was derived via EWMA (smoothed load). This approach uses a decay factor λ (lambda; value between 0 and 1), accounting for the decaying nature of load by assigning a higher weighting factor to more recent sessions (Hunter, 1986).

The cumulative load was calculated by λ × (the previous day's internal load) + (1 – λ) × (the cumulative internal load up to that point). The resulting cumulative load is effectively smoothed with the time constant given by the ratio 1/ λ (λ = 1 over the number of days) (Lazarus et al., 2017). The smoothed load for this study was generated with λ of 0.33, 0.14, 0.1, 0.07 and 0.04 (representing time constants of 3, 7, 10, 14 and 28 day; d periods respectively).

Match performance was determined via coaching and fitness staff (1 head coach, 2 assistant coaches, 1 goal keeping coach and 1 high performance manager) providing a rating of each player's performance in fulfilling their assigned role throughout the match using a 1-5 rating scale (1 = poor through to 5 = excellent) (Mooney et al., 2013a). The mean of the 5 ratings was assigned to each player's individual match performance.

Athlete's countermovement jump (CMJ) and saliva collection were conducted before the last training session prior to match play (match day -1). Athletes were familiarized with the CMJ and saliva collection procedures prior to data collection. A CMJ for maximum height was performed on a force plate (400 Series Platform Plate; Fitness Technology, Adelaide, Australia) connected to manufacturer-supplied software (Ballistic Measurement System; Fitness Technology, Adelaide, Australia) according to established protocols (Cormack et al., 2008a). The ratio of flight time to contraction time (FT:CT) is the measure most sensitive to variations in load in this cohort, and was therefore used for analysis (Cormack et al., 2008c). Athletes provided 2 mL of saliva using the unstimulated passive drool technique between 0900 hrs – 0930 hrs following strict pre-test procedures (Cormack et al., 2008a). Samples were immediately frozen for later analysis. Duplicate enzyme-linked immunosorbent assay (Salimetrics, PA, USA) using a microplate reader (SpectraMax 190, Molecular Devices, CA, USA) determined testosterone [pg.mL-1] and cortisol [μg.dL-1] concentration (Cormack et al., 2008a).

Data were analysed using quadratic mixed models in the Statistical Analysis System (version 9.4, SAS Institute, Cary NC). The quadratic model allowed for a curvilinear effect of internal load on match performance (coach rating) and on each of the pre-match test measures (FT:CT ratio, testosterone, cortisol and testosterone:cortisol ratio). Similar models allowed for a curvilinear effect of each pre-match measure on match performance. Fixed effects in the models were the intercept, the predictor (internal load or test measure), and the square of the predictor, which collectively estimated the mean quadratic effect. The random effects were player identity (to estimate different between-player means across the season), the interaction of player identity with the predictor and its square (to estimate individual differences in the quadratic effect), and the residual error (within-player weekly match or test variability). Effects of illness were adjusted for by including a dummy variable representing whether the player reported illness on the day of assessment as a fixed effect and as a random effect interacted with player identity. Separate analyses were performed for each playing position, given the scope of this study was to provide insight into the impact relative to different positions within a team environment.

The quadratic effect of each predictor was assessed by deriving a within-player SD of the predictor by taking the square root of the mean of the squares on each individual player's SD (weighted by degrees of freedom). The effects of a change in the predictor from -1 SD up to the mean and from the mean to +1 SD above the mean were then derived (Lazarus et al., 2017).

Effects on coach rating were derived and reported in raw units. Effects on pre-match test measures were derived after log transformation then back-transformed and expressed in percent units. Effects were assessed using non-clinical magnitude-based inference (MBI) (Batterham and Hopkins, 2006). The uncertainty in the effect was expressed as 90% confidence limits and with likelihoods (%) that the true value of the effect represented substantial or trivial changes expressed as possibly (25-75%), likely (75-95%), very likely (95-99.5%) and most likely (>99.5%) (Hopkins et al., 2009). When the confidence interval (the lower to upper confidence limit) for a change included substantial positive and negative values, the effect was deemed unclear. Given the inflation of overall Type-I error arising from large number of effects presented in this study, only those effects clear with 99% confidence intervals (shown in bold in the tables) were regarded as definitive. The smallest standardised change was considered to be 0.2, with standardised effects classed as: small, 0.20 – 0.60; moderate, 0.60 – 1.20; large, 1.2 – 2.0; very large, 2.0 – 4.0; and extremely large, >4.0 (Hopkins et al., 2009).

5.3 Results

To provide a visual representation of the results of the quadratic analysis, Figure 5.1 displays the change in coach rating for a 1 SD increase in internal load (from 1 SD below the mean to the mean and from the mean to 1 SD above the mean), across the EWMA time-periods for each playing position. Whilst a quadratic shape was fitted to the data to allow for non-linear relationships, the pure distribution of individual players' change in coach rating for a given change in internal load is displayed in scatter plots in Figure 5.2 (14 day EWMA smoothed load chosen for the example). There was little indication of individual differences in the quadratic relationships.

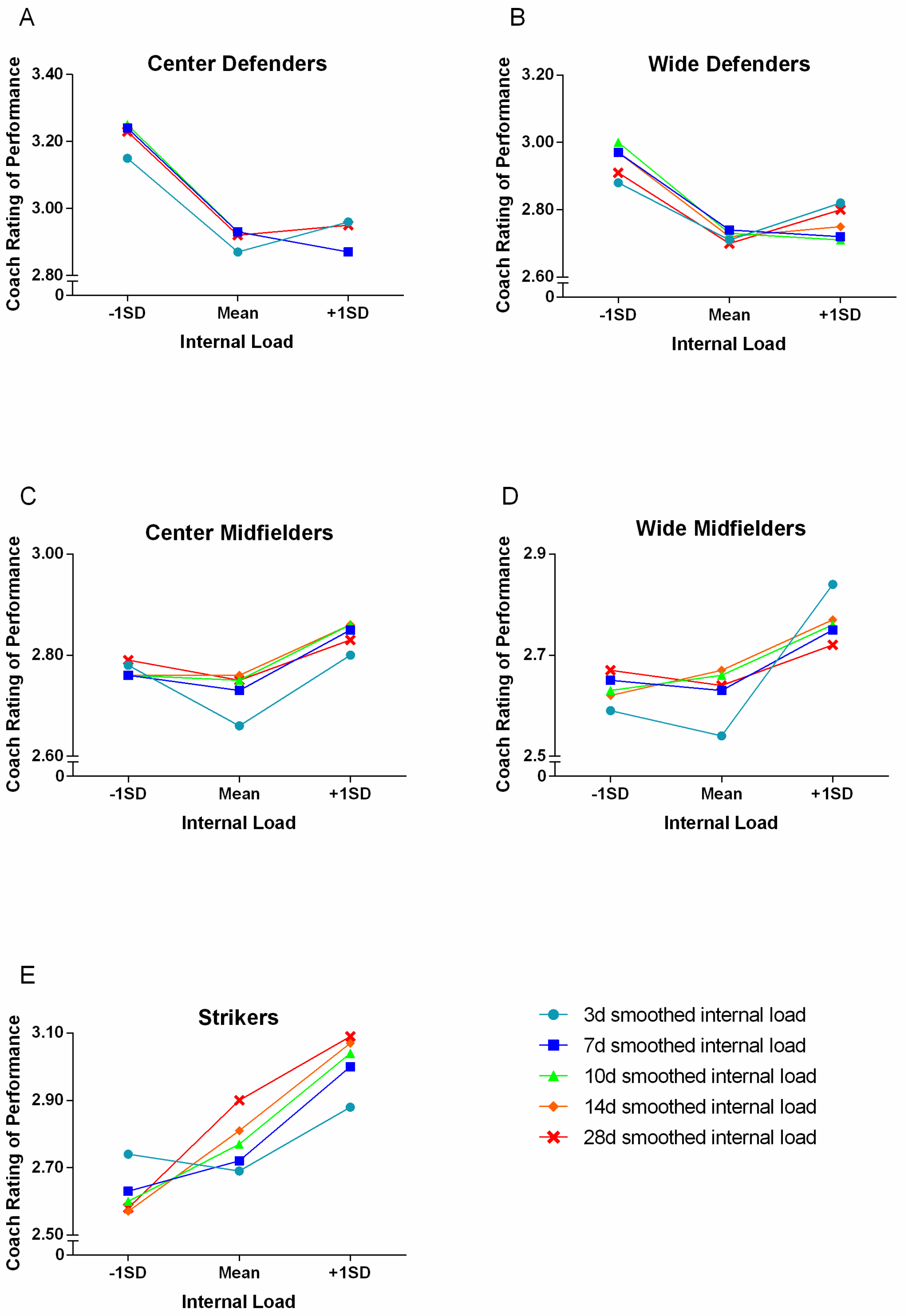

Figure 5.1 Quadratic analysis of the change in coach rating for a given change in internal load ±1 SD from the mean for (A) centre defenders, (B) wide defenders, (C) centre midfielders, (D) wide midfielders and (E) strikers.

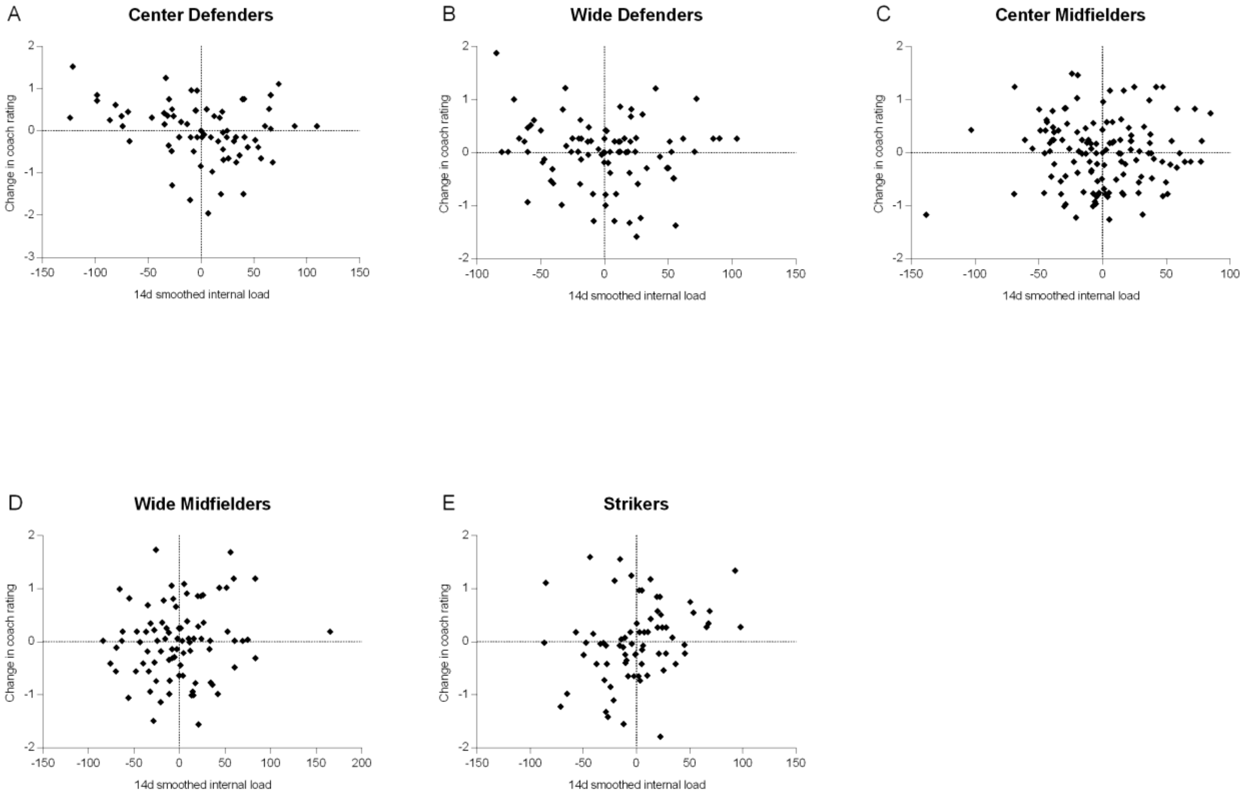

Figure 5.2 Scatter plot distribution of the change in coach rating for a given change in 14 day smoothed internal load for the different playing positions of (A) centre defenders, (B) wide defenders, (C) centre midfielders, (D) wide midfielders and (E) strikers.

The impact of internal load on coach rating of performance is displayed in Table 5.1 with a number of substantial effects (small) observed. Centre defenders showed a very likely reduction in coaches' votes when 3d and 14d smoothed load increased from -1 SD to the mean. Wide midfielders displayed a likely increase in coach rating when 3d smoothed load increased from the mean to +1 SD above the mean. Similarly, strikers displayed a likely increased coach rating when smoothed load increased to +1 SD above the mean for the 7d and 10d periods. There were numerous possible, trivial or unclear effects of an increase in internal load from the mean to ±1 SD above, particularly for centre and wide defenders.

Similarly, there were a large number of unclear interactions between the change in pre-match FT:CT, testosterone, cortisol, and testosterone:cortisol and rating of match performance (Table 5.2). The only clear (small) effect was observed in the wide midfielders, where an increased coach rating was associated with a *likely* increase in testosterone from -1SD up to the mean. The impact of smoothed load on FT:CT was mostly unclear or trivial. However, a small effect was observed in the centre defenders who showed a likely higher FT:CT when 14d smoothed load increased from the mean to +1 SD above the mean. In contrast to the limited impact on FT:CT, cortisol was substantially influenced by internal load. Centre midfielders had a very likely increased cortisol when 7d and 10d smoothed load increased from -1 SD to the mean (small effects). Centre defenders had a most likely increase in cortisol when 3d smoothed load increased from the mean to +1 SD above the mean (large effect). Further, increased 14d and 28d smoothed load from -1 SD to the mean and from the mean to +1 SD above the mean resulted in increased cortisol (small and moderate effects respectively). Wide defenders cortisol likely increased when 10d and 14d smoothed load increased from the mean to +1 SD above the mean (small effects). Wide midfielders also had a very likely increased cortisol with an increase in 28d smoothed load from -1 SD to the mean (small effect).

Centre defenders had a very likely (moderate effect) and likely (small effect) increase in testosterone when 3d and 28d smoothed load increased from the mean to +1 SD above the mean respectively. Wide midfielders also had a very likely and likely increased testosterone (small effects) when 28d smoothed load increased from -1 SD to the mean and from the mean to +1 SD above the mean respectively.

Increased internal load resulted in several substantial reductions in testosterone:cortisol. Specifically, centre defenders had a very likely reduction when 3d and 7d smoothed load increased from the mean to +1 SD above the mean (large effects). Wide defenders had the same response with a likely reduction in testosterone:cortisol when 10d and 14d smoothed load increased from the mean to +1 SD above the mean (small effects). Centre midfielders also had a reduced testosterone:cortisol when 7d, 10d and 14d smoothed load increased from -1 SD to the mean (small effects).

Table 5.1 Mean internal load across each smoothed time window and the corresponding coach rating in each positional group. The raw change in coach rating for a given increase in internal load from -1 SD up to the mean and from the mean to +1 SD above the mean.

	Internal load (mean ± within-subject SD)	Coach rating at mean (mean ± between-subject SD)	Change in coach rating -1 SD to mean (mean, ±90%CL)	Change in coach rating mean to +1 SD (mean, ±90%CL)
3 Day smoothed internal load				
Central Defender	246 ± 58	2.87 ± 0.65	**-0.28, ±0.14*** **	0.09, ±0.22*
Wide Defender	235 ± 73	2.71 ± 0.66	-0.18, ±0.26*	0.11, ±0.26
Central Midfield	232 ± 52	2.66 ± 0.64	-0.11, ±0.12*	0.14, ±0.12*
Wide Midfield	251 ± 59	2.54 ± 0.77	-0.05, ±0.15^{00}	**0.29, ±0.20** **
Striker	233 ± 66	2.69 ± 0.76	-0.05, ±0.15^{00}	0.18, ±0.23*
7 Day smoothed internal load				
Centre Defender	246 ± 52	2.93 ± 0.64	-0.30, ±0.41**	-0.06, ±0.30
Wide Defender	240 ± 51	2.74 ± 0.62	-0.24, ±0.29*	-0.02, ±0.26
Central Midfield	237 ± 41	2.73 ± 0.66	-0.03, ±0.10^{000}	0.13, ±0.12*
Wide Midfield	254 ± 46	2.63 ± 0.79	-0.02, ±0.20	0.12, ±0.15*
Striker	237 ± 47	2.72 ± 0.75	0.09, ±0.15*	**0.28, ±0.21** **
10 Day smoothed internal load				
Centre Defender	247 ± 51	2.93 ± 0.64	-0.32, ±0.34**	-0.06, ±0.30
Wide Defender	244 ± 46	2.73 ± 0.62	-0.26, ±0.30**	-0.02, ±0.27
Central Midfield	239 ± 39	2.75 ± 0.66	-0.01, ±0.10^{0000}	0.12, ±0.11*
Wide Midfield	257 ± 44	2.66 ± 0.79	0.03, ±0.20	0.10, ±0.14*
Striker	240 ± 42	2.77 ± 0.73	0.17, ±0.27*	**0.28, ±0.23** **
14 Day smoothed internal load				
Centre Defender	249 ± 51	2.93 ± 0.65	**-0.31, ±0.15*** **	-0.06, ±0.18^{00}
Wide Defender	248 ± 42	2.72 ± 0.62	-0.25, ±0.27**	0.03, ±0.25
Central Midfield	242 ± 38	2.76 ± 0.66	-0.00, ±0.16	0.11, ±0.24*
Wide Midfield	259 ± 44	2.67 ± 0.79	0.05, ±0.21	0.10, ±0.14*
Striker	244 ± 39	2.81 ± 0.72	0.24, ±0.24**	0.25, ±0.24**
28 Day smoothed internal load				
Centre Defender	255 ± 52	2.92 ± 0.66	-0.31, ±0.25**	0.03, ±0.36
Wide Defender	257 ± 33	2.70 ± 0.63	-0.21, ±0.22*	0.10, ±0.22*
Central Midfield	248 ± 35	2.75 ± 0.66	-0.04, ±0.11^{00}	0.08, ±0.10^{00}
Wide Midfield	266 ± 44	2.64 ± 0.78	-0.03, ±0.23	0.08, ±0.14^{00}
Striker	251 ± 33	2.90 ± 0.71	**0.32, ±0.25** **	0.19, ±0.24*

90%CL: 90% confidence limits.

Values in bold represent substantial effects clear at the 99% level. Symbols denote:*possibly, ** likely, *** very likely and **** most likely chance of the true effect being a substantial change (standardised effect > 0.20). Trivial effects are classified: ^{0}possibly, ^{00}likely, ^{000}very likely and ^{0000}most likely. Unclear effects do not have a symbol.

Table 5.2 Mean coach rating of performance and the raw change in coach rating for a given increase in season average FT:CT, cortisol, testosterone amd testosterone:cortisol from -1 SD to the mean and from the mean to +1 SD above the mean relative to position.

	Coach rating at mean (mean ± between-subject SD)	Change in coach rating -1 SD to mean (mean, ±90%CL)	Change in coach rating mean to +1 SD (mean, ±90%CL)
Change in performance for a given value of FT:CT relative to mean			
Centre Defender	2.98 ± 0.74	-0.28, ±0.36**	-0.25, ±0.31**
Wide Defender	2.67 ± 0.54	-0.06, ±0.29	0.05, ±0.39
Central Midfield	2.93 ± 0.52	0.01, ±0.14	-0.07, ±0.11^{00}
Wide Midfield	2.42 ± 0.60	-0.25, ±0.23**	-0.08, ±0.24
Striker	3.12 ± 0.80	0.11, ±0.57	0.01, ±0.82
Change in performance for a given value of cortisol relative to mean			
Centre Defender	2.92 ± 0.75	-0.12, ±0.25	-0.20, ±0.34
Wide Defender	3.08 ± 0.47	0.12, ±0.43	-0.10, ±0.42
Central Midfield	2.97 ± 0.55	-0.04, ±0.25	-0.09, ±0.27
Wide Midfield	2.91 ± 0.67	0.24, ±0.44	0.01, ±0.46
Striker	3.04 ± 0.61	0.06, ±0.30	0.03, ±0.30
Change in performance for a given value of testosterone relative to mean			
Centre Defender	2.96 ± 0.75	0.03, ±0.24	-0.00, ±0.23
Wide Defender	3.09 ± 0.51	0.04, ±0.31	-0.07, ±0.34
Central Midfield	2.86 ± 0.54	0.04, ±0.18	0.03, ±0.19
Wide Midfield	2.98 ± 0.70	**0.29, ±0.22****	0.11, ±0.13*
Striker	3.00 ± 0.64	0.14, ±0.27	0.16, ±0.64
Change in performance for a given value of T:C relative to mean			
Centre Defender	2.93 ± 0.71	0.25, ±0.31**	0.12, ±0.26
Wide Defender	3.11 ± 0.46	0.11, ±0.25	-0.14, ±0.17*
Central Midfield	2.99 ± 0.58	0.13, ±0.15*	-0.00, ±0.12
Wide Midfield	3.04 ± 0.61	0.18, ±0.40	-0.18, ±0.39
Striker	3.02 ± 0.55	0.11, ±0.34	0.12, ±0.27

90%CL: 90% confidence limits.

Values in bold represent the substantial effects that are clear at the 99% CI. Symbols denote: *possibly, **likely, ***very likely and ****most likely chance that the true effect is a substantial change (standardised effect > 0.20). Trivial effects are classified: ^{0}possibly, ^{00}likely, ^{000}very likely and ^{0000}most likely. Unclear effects do not have a symbol.

5.4 Discussion

The quadratic analysis utilised in this study revealed that across playing positions, mean cumulative internal load was not associated with the best match performance. Furthermore, the relationship between internal load and match performance was impacted by the length of the analysis window with 3 – 14 day periods most influential. This finding indicates that recent load is relatively more important to the performance of high level football players than load accumulated over longer periods. Acknowledging that dividing the sample into playing positions resulted in a small number of participants for each position, combined with minimal variation in training load between individuals within a position, resulted in a limited ability to estimate individual responses.

5.4.1 Interaction between internal load and match performance

Centre defenders had a substantial reduction in coach rating when internal load increased from -1 SD below to the mean in the 3 and 14 day windows. Although centre defenders cover the lowest relative distances ($m.min^{-1}$) and also have the lowest internal load compared to the other playing positions during matches (Torreño et al., 2016), a large proportion of match load in this group is accumulated through body contacts and other movements apart from running (Arrones et al., 2014, Torreño et al., 2016, Bloomfield et al., 2007, Dellal et al., 2010). These movements (that are independent of running) potentially induce high levels of muscle damage and/or neuromuscular fatigue, resulting in the need for a longer recovery time (Bloomfield et al., 2007, Johnston et al., 2014a). As a result of the greater non-running stress, players in this positional group may benefit from a reduced training load in order to allow them to recover from each match. Furthermore, given their tactical role and associated importance of maintaining defensive structure and organisation to prevent the opposition forwards from scoring, centre defenders may have a higher psychological load compared to the other positions (Dellal et al., 2010). This psychological load is likely to be a substantial contributing factor to their RPE (Blanchfield et al., 2014, Gallo et al., 2015) and further supports the suggestion that this position is likely to benefit from relatively lower training loads in the immediate pre-match period. Whist reductions in coach rating were found with increases in load across all EWMA periods, the most pronounced effects were observed in the 3 day and 14 day windows (-0.28 ±0.14 and -0.31 ±0.15). This suggests that planning the training load of centre defenders may be best achieved by manipulating 3 day and 14 day periods and ensuring their load is not greater than -1 SD below the mean. Wide defenders displayed a similar pattern of lower match performance from increasing internal load and may be the result of similar match activity profiles to those of centre defenders (Torreño et al., 2016, Di Salvo et al., 2007). Due to their tactical requirements in match play, wide defenders' biggest contribution to load however, occurs through repeat high-intensity efforts and sprints as they provide an overload wide passing option (Torreño et al., 2016, Arrones et al., 2014). The findings for the wide defenders suggests a training load monitoring and manipulation approach similar to that adopted for centre defenders (i.e. lower training loads) may be appropriate.

In contrast to defenders, wide midfielders and strikers displayed increased coach ratings when internal load was +1 SD above the mean. The largest effects occurred across the more acute windows of 3 day EWMA for wide midfielders, and 7 day and 10 day EWMA periods for the strikers. It appears, like the defenders, there is an incongruity between mean training load and match performance. As midfielders generally produce the highest match activity profiles (Di Salvo et al., 2007, Arrones et al., 2014, Torreño et al., 2016), the mean training load in this study may have been an insufficient stimulus to prepare this positional group for match play. Despite the relationships between internal load and performance being seemingly opposite in defenders compared to midfielders, it appears that monitoring training load should occur across a similarly short window. In the case of midfielders, optimising training may be best achieved by using a window of 3-10 days. It appears that more chronic training load (i.e. longer than 10 days) is relatively unimportant in acute match performance, however there may be interactions with other aspects such as injury (Hulin et al., 2016, Malone et al., 2016).

5.4.2 Impact of FT:CT and testosterone, cortisol and testosterone:cortisol on coach rating of performance

The ratio of FT:CT provides a useful marker of altered movement strategy as a result of neuromuscular fatigue (Cormack et al., 2008a). A reduction in pre-match FT:CT of >8% moderated the movement effeciencey of Australian rules football players in subsequent match play and resulted in a lower coach rating of performance (Mooney et al., 2013a, Cormack et al., 2013). Furthermore, a reduction in FT:CT post-match compared to baseline was also negatively correlated with subsequent match performance (Cormack et al., 2008b). However, despite a moderate to high accumulated PlayerLoad™ (>500 au) during elite football match play being shown to cause suppressed FT:CT for 42 hours (chapter 3), in the current study many of the associations between FT:CT and coach rating of subsequent performance were unclear. Whilst FT:CT provides a useful recovery measure in this population (chapter 3), it did not display a clear impact on performance as measured by coach rating in this study. The current findings may be a function of a shorter neuromuscular recovery in A-League players (42 hours) (chapter 3) compared to Australian Rules (72 hrs) (Cormack et al., 2008a). Due to this, although players may have been classed as "fatigued" based on their FT:CT on match day -1, they may have been nearly fully recovered by match time (~36 h post FT:CT assessment). As a result, the FT:CT value on match day -1 may not have been a true reflection of suppressed neuromuscular function during the match. Although FT:CT assessed on match day -1 may not be directly related to coach rating of performance in football players, it may act as a moderator of movement strategy (Mooney et al., 2013a, Cormack et al., 2013), however this is yet to be explored in football players.

Higher pre-match testosterone has been associated with improved match performance in other football codes such as Australian Rules and rugby (Cormack et al., 2008b, Cook and Crewther, 2012). Similarly, wide midfielders in the current study had an increased rating of match performance when testosterone increased from -1 SD to the mean; however, no clear interaction was evident in the other positions. Increased testosterone may also reflect regeneration and recovery from previous load (Carré et al., 2006, Crewther et al., 2013). Heightened pre-match testosterone is associated with preparatory, aggressive and dominant behavior increasing assertiveness and vigor leading to a dominant and winning performance (Crewther et al., 2013, Kraemer et al., 2004, Argus et al., 2009, Martínez et al., 2010, Gaviglio et al., 2014b). The elevation of testosterone that occurred in the wide midfielders when internal load was above the mean may have improved performance through similar mechanisms. It appears that a higher training load in this positional group may provide an anabolic stimulus that subsequently impacts performance (Meckel et al., 2011, Kilian et al., 2016). In contrast, the lack of interaction with performance appears to somewhat limit the usefulness of both cortisol and testosterone:cortisol for regular performance monitoring in A-League football, however substantial relationships with previous training load may suggest some benefit for their use (see below).

5.4.3 Impact of internal load on FT:CT and hormonal response

Whilst external load impacts the post-exercise response of various performance and biochemical markers (Cormack et al., 2008a, Tofari et al., 2017), prior internal load has also demonstrated an influence. For example, the increase in internal load (RPE-based) from basketball match play was closely correlated to an increase in post-match cortisol response (r =0.75) (Moreira et al., 2012).

In the current study, the interaction between internal load and FT:CT was predominantly unclear. This was similar to the impact of the change in FT:CT on performance. However, a clear effect was evident in centre defenders, where an increase in internal load by +1 SD above the mean 14 day EWMA resulted in a likely increase in FT:CT. Paradoxically, increased internal load in the same positional group and time period was associated with lower performance ratings. Whilst it appears that an elevated training load provides some kind of stimulating effect on jumping performance, it also negatively impacts coach perceptions of performance. The exact mechanism at play here is unclear and requires further investigation. Furthermore, it must be acknowledged the muli-faceted nature of a coaches perception of performance and can involving both physical and mental output.

Testosterone is an anabolic hormone that has been shown to increase across a competitive Australian Rules football season (Cormack et al., 2008b). Such a response suggests team sport players may be able to maintain an anabolic hormonal environment even during long competitive seasons. Similarly, testosterone increased in response to a single match in A-League football players (chapter 3) and the results of the current study are in agreement for wide midfielders and centre defenders with an increased testosterone over the 28 day EWMA window. The increase in testosterone that occurs when training load increases +1 SD above the 28 day mean suggests that a relatively high chronic training load plays a role in creating an anabolic environment in these athletes (Cormack et al., 2008b, Kraemer et al., 2004). Similarly, the increase in testosterone in the group of centre defenders, as a result of elevated 3 day internal load suggests that the acute training stimulus also creates such an anabolic stimulus (Urhausen et al., 1995, Eliakim et al., 2009). As a result, it appears that increasing the training load above the mean for centre defenders in particular, has a beneficial effect on hormones, however this does not coincide with performance improvements.

A change in internal load from -1 SD below to the mean and from the mean to +1 SD above was associated with increased cortisol in wide midfielders and both defensive groups across various EWMA windows. This finding is similar to previous work in professional basketball players, where heightened cortisol was related to session RPE (r = 0.75) (Moreira et al., 2012). Cortisol is a stress hormone, that has increased in response to training and match load in team sport athletes (Filaire et al., 2003)(chapter 3). In the case of centre defenders, increasing internal load appears to result in both an increase in cortisol and compromised performance. This may be a function of both the physiological and psychological stress associated with playing and training for defensive players and further supports the notion that a relatively lower training load would be beneficial.

A decreased testosterone:cortisol ratio, particularly in excess of 30% is suggested to be reflective of a catabolic state (Viru and Viru, 2004). A-League match play results in a reduced testosterone:cortisol (Chapter 3) and the current findings suggest increased training loads above the mean substantially reduce testosterone:cortisol, particularly in defensive players. Examination of the individual testosterone and cortisol response suggests in many cases there has been an increase in testosterone, however this can be outweighed by an increase in cortisol and result in a decreased testosterone:cortisol (Hayes et al., 2015). Furthermore, as mentioned above, the lack of association between testosterone:cortisol and performance in the current study casts doubt on the suitability of testosterone:cortisol as a regular monitoring tool for associated match performance in A-League Football players.

5.5 Conclusions and practical applications

The impact of internal load on performance in A-League players appears to be individual and position specific. Wide-midfielders and strikers performance is enhanced with internal load above the overall team mean, whilst central defenders appear to benefit from a relatively lower internal load. It appears in this population that relatively recent training load (i.e. 3 – 14 days) is more important to match performance than load accumulated over longer periods.

The hormonal response to internal load appears to be impacted by both very short (3 day) and relatively long (28 day) preceding workloads. Both these periods stimulate an increase in testosterone, although this was only associated with improved performance in wide midfielders. Furthermore, there are a large number of unclear effects on FT:CT as a result of changes in training load. A similar pattern exists in relation to changes in performance due to changes in FT:CT and hormonal variables. Based on the current results the use of testosterone, cortisol and FT:CT as indicators of subsequent performance is questionable, however this may be impacted by the timing of testing relative to match play. Furthermore, the division of the sample into playing positions resulting in a small sample size for each position, combined with minimal variation in training load between individuals within a position may result in a limited ability to estimate individual responses.

Within the scope of the acknowledged limitations, the results of this research suggest that improving performance in A-League players may be assisted by the manipulation of training load on a position-specific basis. Specifically, coaches and support staff could maximise the performance of strikers by closely monitoring load and potentially providing a workload above the 7 day and 10 day mean internal load. Similarly, the performance of wide midfielders may be enhanced by increasing load above the 3 day smoothed mean. Conversely, centre defenders training loads might be reduced below their respective mean internal loads for the relevant length windows. In order to achieve this, coaches and support staff should monitor internal training load via the use of session RPE and calculate the smoothed load using a EWMA for relatively short time constants (i.e. 3 – 14 days). Subsequent training can then be adjusted to achieve the desired internal load.

CHAPTER 6. LINK BETWEEN STUDY 2 AND 3

Study 2 explored the impact of prior competition load on neuromuscular recovery and salivary hormones and subsequent match performance. It was evident from the results that differing windows of load exposure (3 – 28 days) impacted athletes match performance according to playing position. It appears that a reduced internal load is related to improved performance in defenders whilst an increased internal load appears to contribute to improvements in performance in attacking players. In addition, the results of this study suggested limited impact of internal load on neuromuscular recovery, however there was a position specific increase in salivary hormone values assessed on the morning prior to match play. In addition, a change in neuromuscular recovery and hormonal profile did not appear to have a clear association with subsequent match performance. As only internal load was quantified in the previous study, it could be that external load is more important in driving the response of hormonal measures and neuromuscular fatigue. Furthermore, the ability to draw conclusions about the interactions between the post-match response and performance may have been impacted by analysis of mean data and the small numbers within each positional group. It is also possible that in this population, neuromuscular fatigue and hormonal variables impact subsequent match activity profile (e.g. a potential change in movement strategy) rather than performance as measured by coaches' votes.

Given these possibilities, Study 3 aimed to explore the impact of prior training and competition load on NMF and the impact on subsequent match activity profile. However, as the collection of FT:CT requires expensive specialist equipment its use may be limited in some environments. As a change in movement strategy in other team sports has been shown following neuromuscular fatigue, it may be that neuromuscular fatigue also manifests as changes in activity profile in a standardised SSG. As a result, this study also aimed to assess whether the activity profile of a standardised small sided game could be used to assess neuromuscular fatigue.

CHAPTER 7. A STANDARDISED SMALL SIDED GAME CAN BE USED TO MONITOR NEUROMUSCULAR FATIGUE IN PROFESSIONAL A-LEAGUE FOOTBALL PLAYERS

7.1 Introduction

Monitoring an athlete's response to training and competition load is important for improving adaptation and reducing the risk of illness and injury (Halson, 2014). Quantification of training and competition load can include measures of internal (e.g. heart rate, rating of perceived exertion (RPE)) and external load (e.g. distance, number of repetitions) (Buchheit, 2014a). The availability of microtechnology devices such as Global Positional Systems (GPS) has made the collection of external load variables such as speed and distance commonplace (Aughey, 2011). However, the data relating to short, high speed efforts has validity and reliability limitations as speed and movement complexity increases (Jennings et al., 2010). In addition, speed and distance metrics fail to account for movements associated with team sports such as changing direction and jumping (Cormack et al., 2013, Barrett et al., 2015). To overcome this, tri-axial accelerometers sampling at 100 Hz have been increasingly used as measures of external load in team sports, with the most commonly utilized metric referred to as PlayerLoad™ (Boyd et al., 2013).

PlayerLoad™, calculated as the sum of instantaneous rate of change from the individual vertical (PlayerLoad™$_{V}$), medio-lateral (PlayerLoad™$_{ML}$) and anterior-posterior (PlayerLoad™$_{AP}$) planes, has high validity and reliability (Cormack et al., 2013, Barrett et al., 2014). The impact of different levels of match activity on neouromuscular fatigue in football have been quantified using PlayerLoad™ (Chapter 3), and the impact of neuromuscular fatigue on individual PlayerLoad™ vectors has also been assessed in Australian Rules Football (Cormack et al., 2013, Mooney et al., 2013b). Furthermore, changes in the contribution of individual vectors to PlayerLoad™ have been studied in both soccer match simulation as well as professional match play (Barrett et al., 2015, Barrett et al., 2016b).

In addition to between-match changes in activity profile, the subsequent physical and psycho-physiological response of athletes to match play has also been reported (Chapter 3) (Cormack et al., 2013, Gescheit et al., 2015). Numerous variables have been measured in high performance sport for this purpose (e.g. neuromuscular fatigue via jump testing and hormonal concentration via saliva); however they require additional time for testing and the use of specialised equipment (Taylor et al., 2012b, Cormack et al., 2013, Mooney et al., 2013b). As changes to the contribution of individual PlayerLoad™ vectors occur when matches are played in the presence of neuromuscular fatigue, it could be predicted that these changes are also evident in training drills (Gescheit et al., 2015, Barrett et al., 2015, Cormack et al., 2013). In fact, standardised field protocols are commonly used for the assessment of autonomic nervous system status (Buchheit et al., 2010b, Buchheit et al., 2012, Buchheit et al., 2008). Given the demonstrated reliability of numerous activity profile metrics during small sided games (SSG), there may be potential for a standardised version of such a drill to be used as a tool to assess neuromuscular function (Stevens et al., 2016). However, the impact of previous training and competition load on SSG activity profile has not been examined. Critically, the impact of neuromuscular fatigue on subsequent match performance has received little attention (Cormack et al., 2008b, Mooney et al., 2011, Andersson et al., 2008).

Increased weekly training load greater than 15% from the previous week is associated with an increased injury risk (Gabbett, 2016b). Whilst it has been suggested that a relatively high acute load increases injury risk, the precise mechanism by which this occurs is unclear. It is possible that relatively high acute load manifests as a modified movement strategy, therefore placing tissue at increased risk of injury (Oliver et al., 2014). Conversely, enhanced team match performance in Australian Rules Football was linked to a higher acute load, and training stress balance, than losses (Aughey et al., 2016). Indeed, the acute training load is said to represent “fatigue” in Banister’s model and may drive adaptation (Aughey et al., 2016, Banister et al., 1975b). These findings suggest there may be a trade-off between injury risk and adaptation/performance; therefore, tracking responses to acute load and potential movement strategy alterations are of particular interest.

Improving the training process is a critical challenge for coaching and sport science support staff in professional football. The ability to assess changes in movement strategy that provides insight into the fatigue status of athletes via a common training drill is an attractive proposition. Given prior work in team sport athletes, it was hypothesised that the presence of neuromuscular fatigue would potentially change the physical output during match play, but it was unknown if this would present in the same way during a standardised training drill. It was also hypothesized that variance in training load had the potential to change the physical output during both training and match play. Therefore, the purpose of this study was to assess:

1) The impact of preceding weekly load on SSG activity profile and match day -1 (the day prior to the match) neuromuscular fatigue.

2) The degree to which a change in match day -1 neuromuscular fatigue impacts SSG activity profile.

3) The impact of match day -1 neuromuscular fatigue and SSG activity profile on subsequent match activity profile.

7.2 Methods and materials

Data were collected from 21 male outfield football players competing in the elite Australian football competition – the A-League. Players had a mean ± SD age; 25.2 ± 5.5 yrs, height; 180 ± 6.7cm and mass; 75.6 ± 5.9 kg. Data was collected from a single competitive season, from players who were signed to the senior team and participated in the weekly match, and therefore provides a case study of this particular club. Ethical approval was granted from Victoria University Human Research Ethics Committee, with written informed consent obtained prior to commencement.

7.2.1 Training structure

Data included in the analysis was collected from a total number of 110 training sessions, and 36 matches across the competition season. One match on average was played per week with 3-4 main training sessions preceding the match. Training load reflects pitch-based skills sessions only; given the weekly (on average <1hr) gym based session was targeted towards injury prevention exercises. The competitive 2015/2016 A-league season spanned over 7 months (October – April). During the latter part of the season (February – May), the team also competed in the Asian Champions League (ACL). The ACL cross-over period resulted in multiple matches played per week and reduced training sessions. There were 7 weeks across the season where the team played two matches per week due to a pre-season FFA cup, a game re-scheduling and the ACL period. The overall training design and implementation was under the control of coaching and fitness staff and was not modified for this study.

7.2.2 External and Internal Load

During each match and training session, athletes wore a global positioning system (GPS) device (OptimEye S5; Catapult Sports, Melbourne, Australia) sampling at 10 Hz, which also housed accelerometers sampling at 100 Hz (Kionix: KXP94). The unit was worn in a custom tight-fitting vest, with athletes assigned the same unit throughout the season. External load variables selected to reflect total weekly volume were: distance (m), high-intensity running (HIR) distance (m >4.2 $m.s^{-1}$) and PlayerLoad™ (au). Following each training session (≈30 min post) athletes recorded their RPE, which was multiplied by the duration of the session or playing time in the match to give session RPE (sRPE) as a measure of internal load (Foster, 1998).

7.2.3 Small-Sided Game

A standardised small-sided game (SSG) drill: 5v5 + 5 + goal keepers (GKs); two teams of five outfield players with a GK each, and the third team of five acting as “bouncers” on the outside of the pitch to keep the ball in play, was performed. The SSG drill was played within a 45 m x 36 m area of the outdoor training pitch and was a free-play style with no restrictions, with the outcome aim to score as often as possible. The SSG was performed after the warm up, at the same point of the weekly cycle; the morning before the training session 1 day prior to the match (matchday -1) which was at least 42 hours after the previous match. The SSG teams were selected by coaching staff. A total number of 4 sets performed, with each team completing 2 sets of 3 min.

7.2.4 Small-Sided Game and Match Activity Profile

The following variables (per minute of activity time) were collected from the match and SSG: metres per minute ($m.min^{-1}$), PlayerLoad™ per minute (PlayerLoad™.min-

^{1}), PlayerLoad™ per meter per minute (PlayerLoad™.m.min^{-1}), PlayerLoad™Slow per minute (movement in all three planes when velocity was <2 m.s^{-1}; PlayerLoad™Slow.min^{-1}), PlayerLoad™ 2D per minute (all movements performed excluding the vertical vector; PlayerLoad™2D.min^{-1}), and the percent contributions of individual PlayerLoad™ vectors [PlayerLoad™$_{AP}$(%), PlayerLoad™$_{ML}$(%) and PlayerLoad™$_{V}$(%)].

7.2.5 Match Day -1 Neuromuscular Fatigue

Prior to the training session that contained the SSG drill, athletes performed a maximal countermovement jump (CMJ) on a force plate (400 Series Platform Plate; Fitness Technology, Adelaide, Australia) connected to manufacturer-supplied software (Ballistic Measurement System; Fitness Technology, Adelaide, Australia). Athletes were familiarised with the CMJ during the pre-season and in line with established protocols, were instructed to jump as high as possible (Cormack et al., 2008a). The flight time:contraction time (FT:CT) ratio is the measure most sensitive to alterations in training and competition load in this cohort, and was therefore used to determine pre-match neuromuscular fatigue status (Chapter 3) (Cormack et al., 2008c).

7.2.6 Weekly Load

To identify the impact of weekly load on SSG and FT:CT they were both performed at the same time during the training microcycle; matchday -1. “Weekly” load was therefore calculated from the preceding matchday -1 session through to the day prior to the SSG training session of the next week. This included one game per “training week”. For each athlete, their individual average weekly volume (total distance, HIR distance, total PlayerLoad™ and internal load (sRPE)) was calculated across the season. To compare the overall team response between a high and low training week, each individuals weekly load was separated in to two groups. Individuals weekly volume was averaged across the season for each metric. A"high" weekly load was then calculated as any week when the individual athletes' load (for each variable) was above their individualised seasonal average and "low" when their weekly load metric was below their season average for each individual variable.

7.2.7 Reliability & Baseline Calculation

The reliability of activity profile variables, represented by the Coefficient of Variation (CV%) (Hopkins, 2017b), was calculated during 5 consecutive pre-season weeks where the SSG was performed on a matchday -1. Based on previous work, the CV% of FT:CT was set at 8% (Cormack et al., 2008c). The average of athletes' 5 pre-season trials was also used to calculate their baseline SSG activity profile variables and FT:CT for later comparison. Figure 7.1 shows a diagrammatic representation of the analysis process described in further detail below.

Data were log-transformed to reduce bias due to non-uniformity of error. The magnitude of the mean difference (high vs. low load and < or > baseline) was calculated using the Effect Size (ES) ± 90% CI. Effects were classified as small; 0.20 – 0.60, moderate; 0.60 – 1.20, large 1.2 – 2.0, very large; 2.0 – 4.0 and extremely large; >4.0. Differences were declared practically important if there was a >75% likelihood of exceeding the smallest important ES of 0.2 threshold of the observed between-subject SD (Hopkins, 2004a). Differences with less certainty were considered trivial, and where the 90% CI crossed substantially positive and negative values the effect was considered 'unclear' (Hopkins, 2004a).

7.2.7.1 Impact of weekly load on SSG activity profile and neuromuscular fatigue

Part 1: For each individual athlete, weekly in-season SSG activity profile (using variables deemed reliable from above) and FT:CT was compared between "high" weekly load (those weeks above the season average) and "low" weekly load (those weeks below season average) using a custom spreadsheet (Hopkins, 2017a). The SSG activity profile metrics that were >75% likely to be different when comparing "high" and "low" load weeks were retained for further analysis (Step 4).

7.2.7.2 Impact of difference in neuromuscular fatigue (FT:CT) on SSG activity profile

Part 2: The difference in SSG activity profile was compared between weeks where an athlete's FT:CT was above or below (to reflect fatigued vs non-fatigued) their pre-season baseline by > 8% CV (FT:CT lower than baseline by > 8.0% was considered "fatigued").

7.2.7.3 Impact of difference in FT:CT and SSG activity profile on match activity profile

Part 3: The impact on match activity profile was compared between weeks where FT:CT was higher or lower than pre-season baseline (average of the 5 pre-season measurements) by more than the 8% CV.

Part 4: In order to compare the impact of differences in SSG activity profile metrics on match exercise intensity using the same approach as was taken for FT:CT (Part 3 above) the difference in match exercise intensity was compared between weeks where the SSG activity profile metrics (retained from Part 1 above) were higher or lower than pre-season baseline by more than the 1.0, 1.5 and 2.0 x CV% for that SSG metric (calculated from SSG reliability trials).

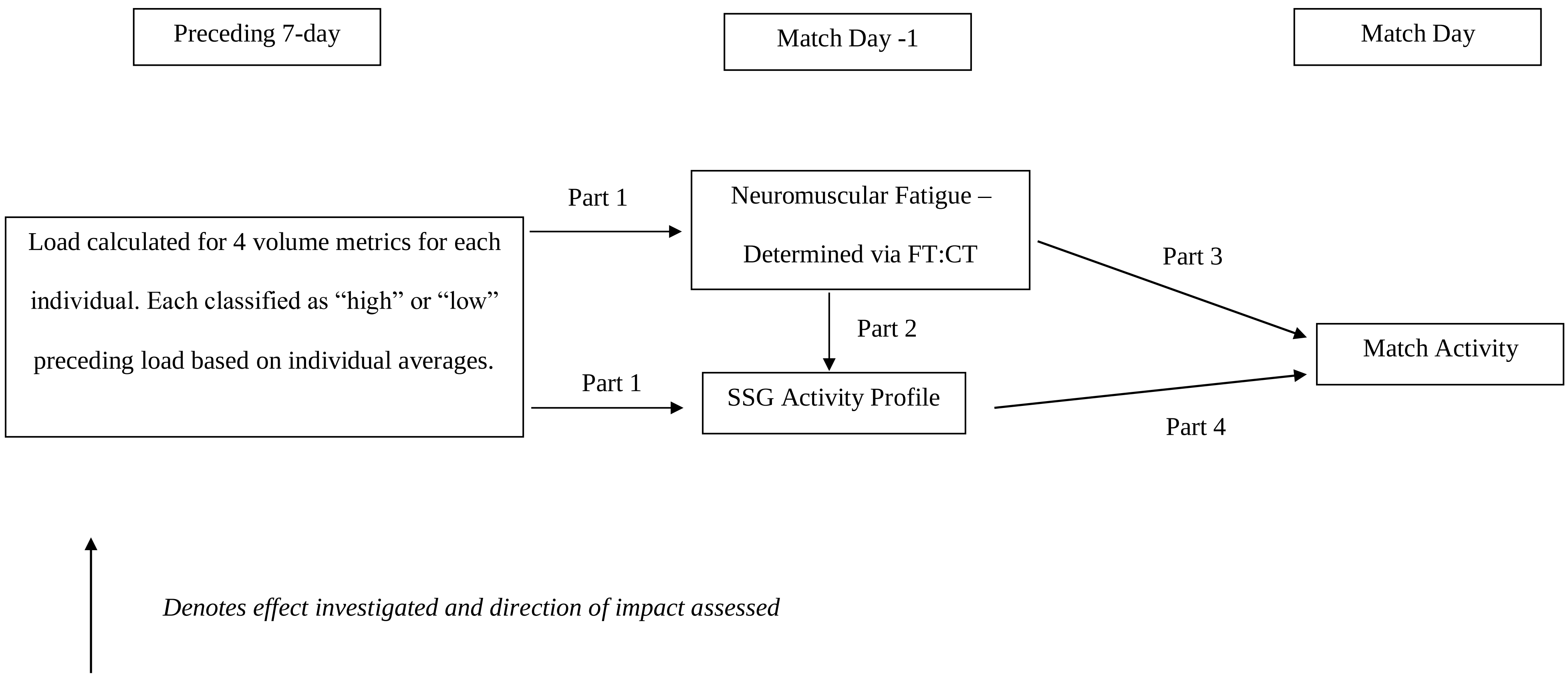

Figure 7.1 Diagrammatic representation of the steps of analysis. Small-sided game; SSG, Flight time:Contraction time ratio; FT:CT.

7.3 Results

7.3.1 SSG Reliability Analysis

The CV% values from the reliability analysis of the SSG were: m.min^{-1}: 4.2%, HIR (>4.2 m.s^{-1}).min^{-2}: 30.6%, PlayerLoad™.min^{-1}: 4.5%, PlayerLoad™.m.min^{-1}: 2.8%, PlayerLoad™2D.min^{-1}: 4.6%, PlayerLoad™Slow.min^{-1}: 8.9%, PlayerLoad™$_{AP}$(%): 3.9%, PlayerLoad™$_{ML}$(%): 2.4%, PlayerLoad™$_{V}$(%): 2.1%. These variables were considered reliable and were used for subsequent analysis, however due to a poor CV of 30.6% (Jennings et al., 2010), HIR.min^{-1} was excluded from further analysis.

Based on the response to high load and the threshold set to determine a substantial worthwhile change in performance (i.e. > 75% likely to be different between weeks above and below season average), the values that displayed the clearest change and therefore retained for analysis from the SSG were PlayerLoad™.m.min^{-1} and PlayerLoad™Slow.min^{-1}.

7.3.2 Impact of Weekly Load on SSG Activity Profile & FT:CT

The average weekly "high" and "low" load values for distance, HIR, PlayerLoad™ and internal load are presented in Table 7.1. The values displayed in Table 7.1 are the team average of each individual athlete's "high" and "low" weeks which was calculated relative to their individualised season average.

Table 7.1 Average weekly total distance, high-intensity running (HIR; >4.2m.s^{-1}), PlayerLoad™ and internal load reflecting "high" load weeks compared to "low" load weeks.

	Total distance (m) (mean ±SD)	HIR (m; >4.2m.s^{-1}) (mean ±SD)	PlayerLoad™ (au) (mean ±SD)	Internal load (au) (mean ±SD)
Team average "high load" > season average	22820 ±2687 m	3047 ±574 m	2402 ±365 au	1930 ± 58 au
Team average "low load" < season average	8132 ±2676 m	841 ±291 m	856 ±299 au	728 ±302 au

The mean ±SD and change (ES ±CI) in SSG activity profile metrics and FT:CT when weekly load was above and below the season average is displayed in Table 7.2. There were a number of substantial changes (small-moderate effects) in SSG metrics as a result of high weekly load. There was a *very likely* increase in PlayerLoad™.m.min^{-1} when all weekly load metrics were above the season average. Similarly, a *very likely* increase in SSG PLSlow.min^{-1} with a higher weekly total distance, PlayerLoad™ and internal load, and *likely* increase from a higher weekly HIR compared to season average. There was also a *likely* increase in PlayerLoad™2D.min^{-1} when weekly total distance, HIR and PlayerLoad™ were above the season average. “High” weekly load metrics caused trivial changes in FT:CT.

Table 7.2 Mean ± SD and change in mean (ES ± 90%CI) in selected SSG activity metrics and FT:CT when weekly load variable was higher than the season average.

Weekly Load Metric	SSG Variable & FT:CT	Mean ±SD when weekly load metric < Season Average "Low Week"	Mean ±SD when weekly load metric > Season Average "High Week"	ES ± 90%CI change in SSG variable
Total distance	$m.min^{-1}$	126.3 ±10.2	125.4 ±11.0	-0.09 ± 0.37
	PlayerLoad™$.min^{-1}$	14.1 ±1.4	14.6 ±1.5	0.33 ±0.28**
	PlayerLoad™$.m.min^{-1}$	0.112 ±0.008	0.117 ±0.008	0.61 ± 0.19***
	PlayerLoad™2D$.min^{-1}$	8.58 ±0.86	8.92 ±0.94	0.38 ± 0.23**
	PlayerLoad™Slow$.min^{-1}$	4.23 ±0.53	4.58 ±0.52	0.60 ± 0.32***
	PlayerLoad™$_{AP}$(%)	26.5 ±2.0	26.4 ±1.5	-0.04 ± 0.27
	PlayerLoad™$_{ML}$(%)	26.0 ±2.0	26.3 ±1.6	0.18 ± 0.15
	PlayerLoad™$_{V}$(%)	47.5 ±2.0	47.3 ±2.0	-0.11 ± 0.19
	FT:CT	0.68 ± 0.12	0.68 ± 0.11	-0.01 ± 0.13
HIR distance (>4.2m.s^{-1})	$m.min^{-1}$	127.0 ± 8.5	124.8 ±10.9	-0.27 ±0.40
	PlayerLoad™$.min^{-1}$	14.3 ±1.2	14.6 ±1.5	0.25 ±0.27
	PlayerLoad™$.m.min^{-1}$	0.113 ±0.008	0.118 ±0.008	0.57 ± 0.20***
	PlayerLoad™2D$.min^{-1}$	8.66 ±0.78	8.92 ±0.94	0.30 ± 0.24**
	PlayerLoad™Slow$.min^{-1}$	4.30 ±0.48	4.58 ±0.56	0.55 ± 0.41**
	PlayerLoad™$_{AP}$(%)	26.5 ±2.0	26.4 ±1.5	-0.05 ± 0.27
	PlayerLoad™$_{ML}$(%)	26.1 ±2.0	26.3 ±1.6	0.08 ± 0.14
	PlayerLoad™$_{V}$(%)	47.4 ±2.0	47.3 ±2.0	-0.09 ± 0.18
	FT:CT	0.68 ± 0.11	0.68 ± 0.11	-0.02 ± 0.13
PlayerLoad™	$m.min^{-1}$	126.1 ±9.9	125.4 ±11.3	-0.08 ± 0.39
	PlayerLoad™$.min^{-1}$	14.1 ±1.4	14.6 ±1.5	0.35 ±0.28**
	PlayerLoad™$.m.min^{-1}$	0.112 ±0.008	0.117 ±0.007	0.58 ± 0.19***
	PlayerLoad™2D$.min^{-1}$	8.57 ±0.87	8.92 ±0.94	0.38 ± 0.23**
	PlayerLoad™Slow$.min^{-1}$	4.24 ±0.55	4.58 ±0.52	0.58 ± 0.33***
	PlayerLoad™$_{AP}$(%)	26.5 ±2.0	26.4 ±1.5	-0.01 ± 0.27
	PlayerLoad™$_{ML}$(%)	26.9 ±1.7	26.5 ±1.6	-0.23 ± 0.23
	PlayerLoad™$_{V}$(%)	47.5 ±2.0	47.3 ±2.0	-0.09 ± 0.19
	FT:CT	0.68 ± 0.12	0.68 ± 0.11	-0.01 ± 0.13
Internal load	$m.min^{-1}$	126.5 ±10.0	125.4 ±10.8	-0.11 ±0.35
	PlayerLoad™$.min^{-1}$	14.2 ±1.4	14.6 ±1.5	0.23 ± 0.28
	PlayerLoad™$.m.min^{-1}$	0.113 ±0.008	0.117 ±0.007	0.44 ± 0.14***
	PlayerLoad™2D$.min^{-1}$	8.68 ±0.90	8.87 ±0.94	0.20 ± 0.25
	PlayerLoad™Slow$.min^{-1}$	4.26 ±0.56	4.52 ±0.45	0.46 ± 0.26***
	PlayerLoad™$_{AP}$(%)	26.7 ±1.6	26.4 ±1.6	-0.19 ± 0.24
	PlayerLoad™$_{ML}$(%)	26.0 ±1.9	26.3 ±1.6	0.15 ± 0.15
	PlayerLoad™$_{V}$(%)	47.3 ±2.0	47.3 ±2.0	0.02 ± 0.14
	FT:CT	0.68 ± 0.12	0.68 ± 0.11	0.04 ± 0.11

Flight time:Contraction time ratio; FT:CT, High-Intensity Running (>4.2m.s^{-1}); HIR, meters per minute; $m.min^{-1}$, per minute; $.min^{-1}$, % contribution of anterior-posterior vector to PlayerLoad™; PlayerLoad™$_{AP}$(%), % contribution of medio-lateral vector to PlayerLoad™; PlayerLoad™$_{ML}$(%) and % contribution of vertical vector to PlayerLoad™; PlayerLoad™$_{V}$(%). Symbols denote a **likely, ***very likely and ****most likely chance of the ES exceeding the smallest important value of 0.2.

7.3.3 Impact of FT:CT on SSG activity profile

A reduction in weekly FT:CT compared to baseline by more than 8% (CV) resulted in a *likely* reduction in SSG PlayerLoad™.min^{-1} and PlayerLoad™Slow.min^{-1}. There were no other practically important changes (Figure 7.2).

7.3.4 Impact of FT:CT on match intensity

A reduction in weekly FT:CT compared to baseline by more than 8% (CV) resulted in a *likely* increase in match PlayerLoad™$_{ML}$(%) and *likely* decrease in match PlayerLoad™$_{V}$(%) (Figure 7.2). There were no other practically important differences.

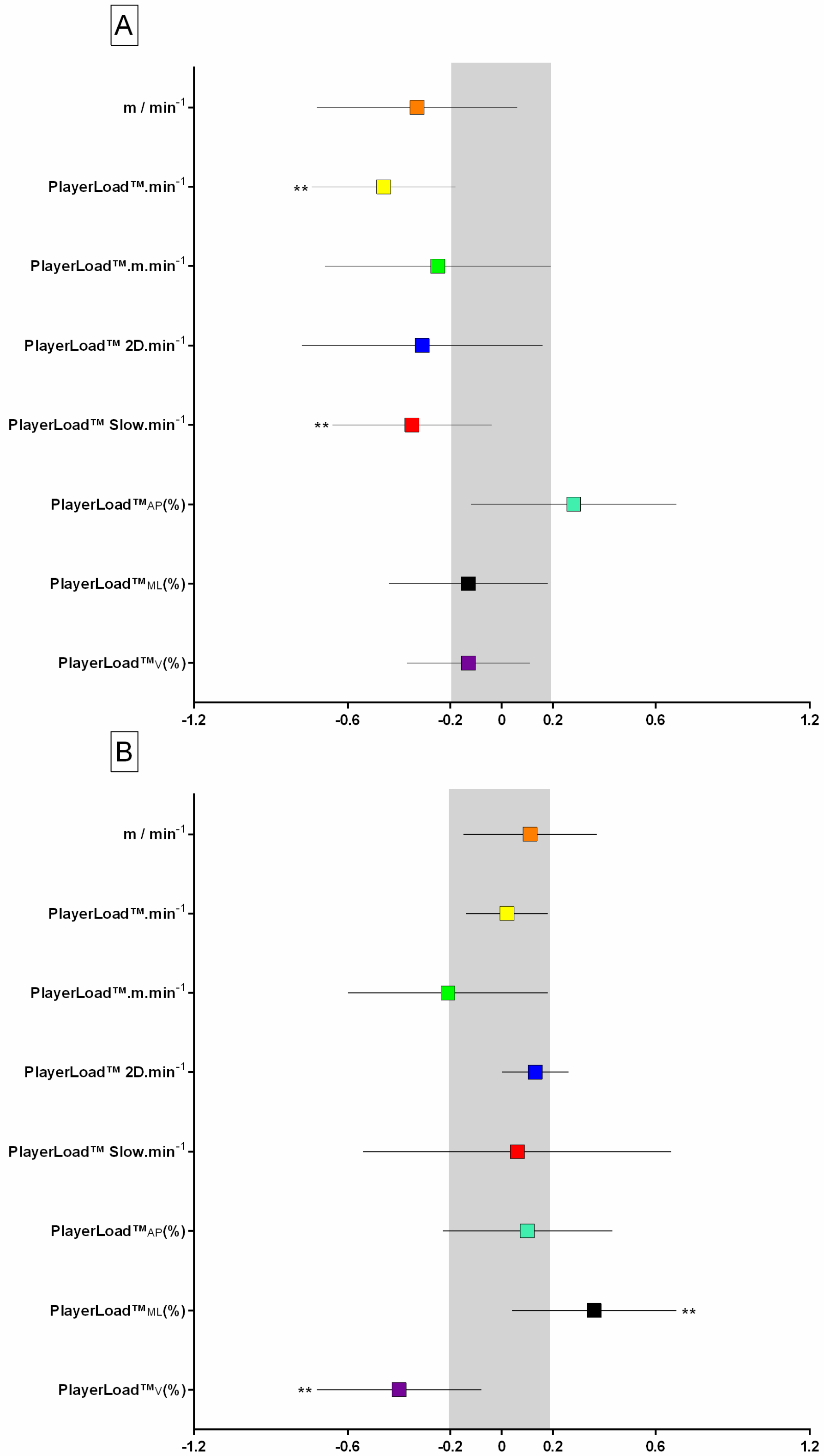

Figure 7.2 Change in SSG activity profile metrics (A) and match exercise intensity (B) based on FT:CT < and > baseline by more than the 8 %CV. Symbols denote alikely, ***very likely and **** most likely chance that the change has exceeded the smallest worthwhile change of 0.2 (shaded in grey).**

7.3.5 Impact of SSG activity profile on match activity profile

The impact of change (as multiples of the CV%) in SSG PlayerLoad™.m.min^{-1} > or < baseline by 1.0, 1.5 and 2 x %CV (calculated independently for each metric) on match exercise intensity is displayed in Figure 7.3. There was a *likely* reduction in PlayerLoad™$_{ML}$(%) when SSG PlayerLoad™.m.min^{-1} was greater than baseline by 1.0 x the %CV. When SSG PlayerLoad™.m.min^{-1} was lower than baseline, by 1.0, 1.5 and 2.0 x the %CV, there was an increased match m.min^{-1} and PlayerLoad™.min^{-1}. Similarly there was an increase in match PlayerLoad™$_{ML}$(%) when SSG PlayerLoad™.m.min^{-1} was lower than baseline by 1.5 and 2.0x %CV.

Figure 7.4 displays the change to match exercise intensity when SSG PlayerLoad™Slow.min^{-1} was < or > baseline by 1.0, 1.5 and 2.0 x the %CV (calculated independently for each metric). When SSG PlayerLoad™Slow.min^{-1} was greater than baseline by 1.5 x the %CV, there was a *likely* higher match m.min^{-1}, PlayerLoad™.min^{-1} and PlayerLoad™.m.min^{-1}. In a similar response, an increase by 2.0 x the %CV resulted in *likely* increased match m.min^{-1}, PlayerLoad™.min^{-1}, and PlayerLoad™2D.min^{-1}, but a *likely* reduction in PlayerLoad™$_{ML}$(%). When SSG PlayerLoad™Slow.min^{-1} was lower than baseline, there was a *likely* increase in match PlayerLoad™$_{ML}$(%). When SSG PlayerLoad™Slow.min^{-1} was lower than baseline by 1.5 and 2.0 x the %CV there was a *very likely* increase in match PlayerLoad™$_{ML}$(%). Figure 7.5 summarises the impact of load on SSG and FT:CT and subsequent impact on match exercise intensity.

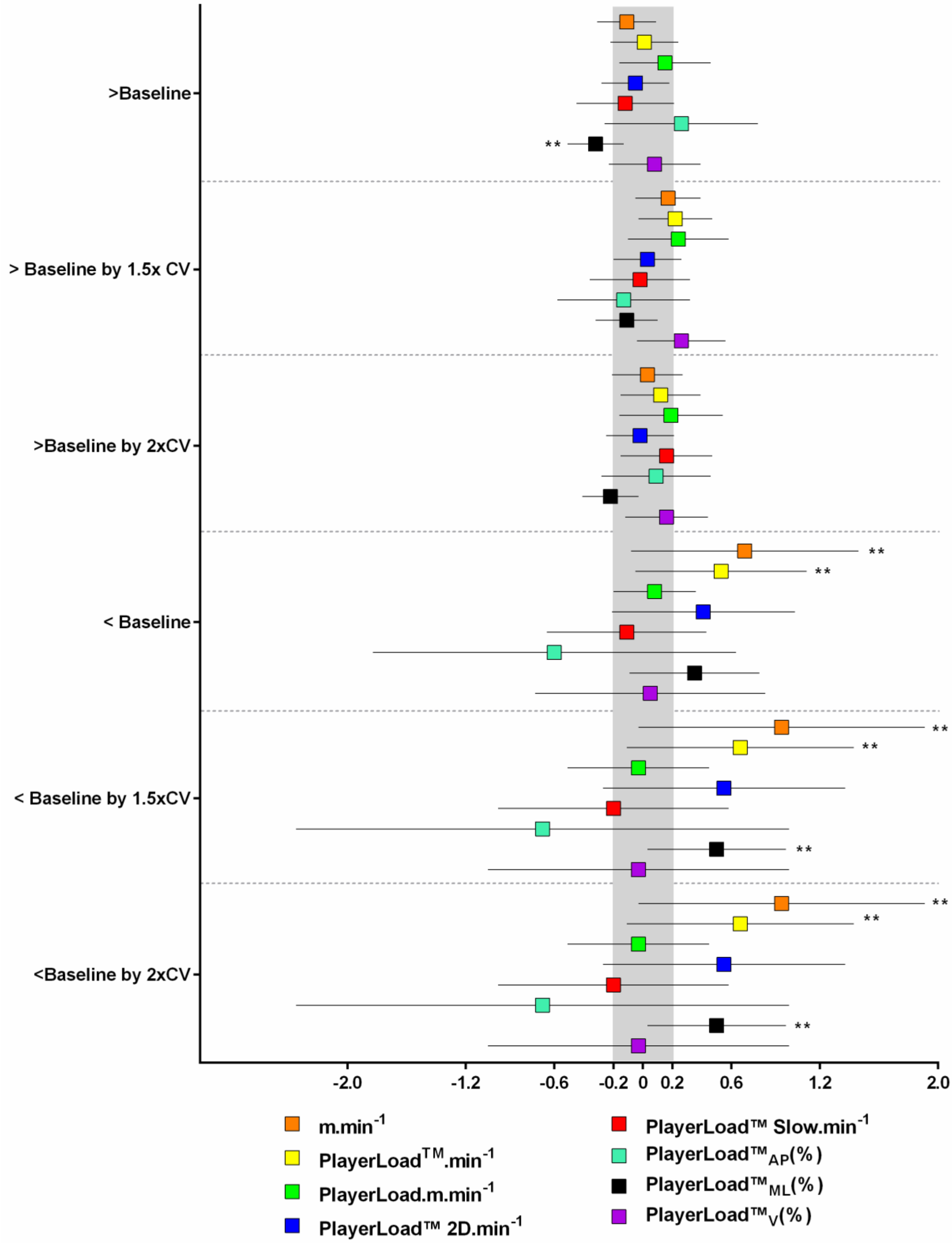

Figure 7.3 Change in match exercise intensity based on SSG PlayerLoad™.m.min^{-1} < and > baseline, by more than 1.0x, 1.5x and 2.0x %CV. Symbols denote a **likely, ***very likely and ****most likely chance that the change has exceeded the smallest worthwhile change of 0.2 (shaded in grey).

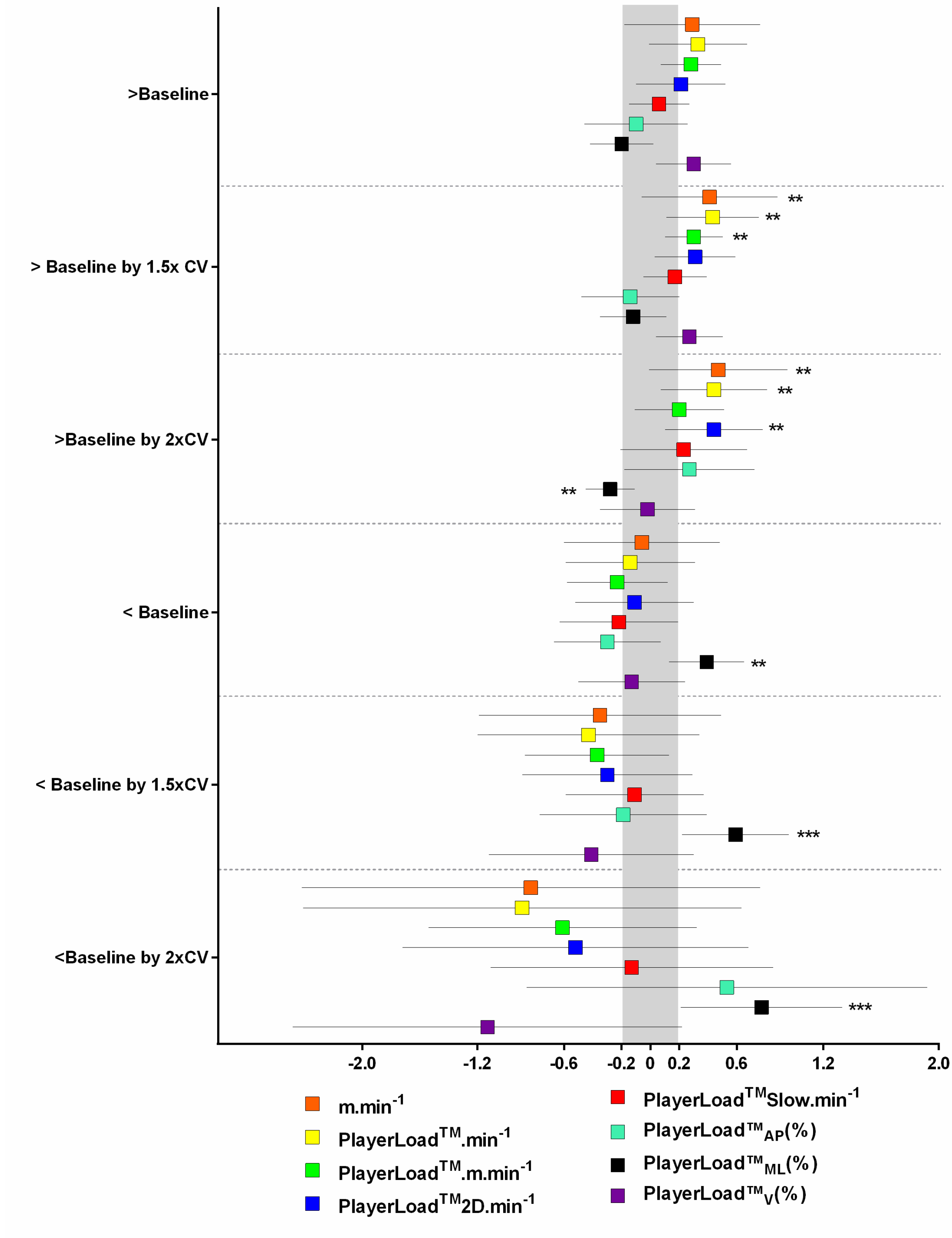

Figure 7.4 Change in match exercise intensity based on SSG PLSlow.min^{-1} < and > baseline, by more than 1.0x, 1.5x and 2.0x %CV. Symbols denote a **likely, ***very likely and ****most likely chance that the change has exceeded the smallest worthwhile change of 0.2 (shaded in grey).

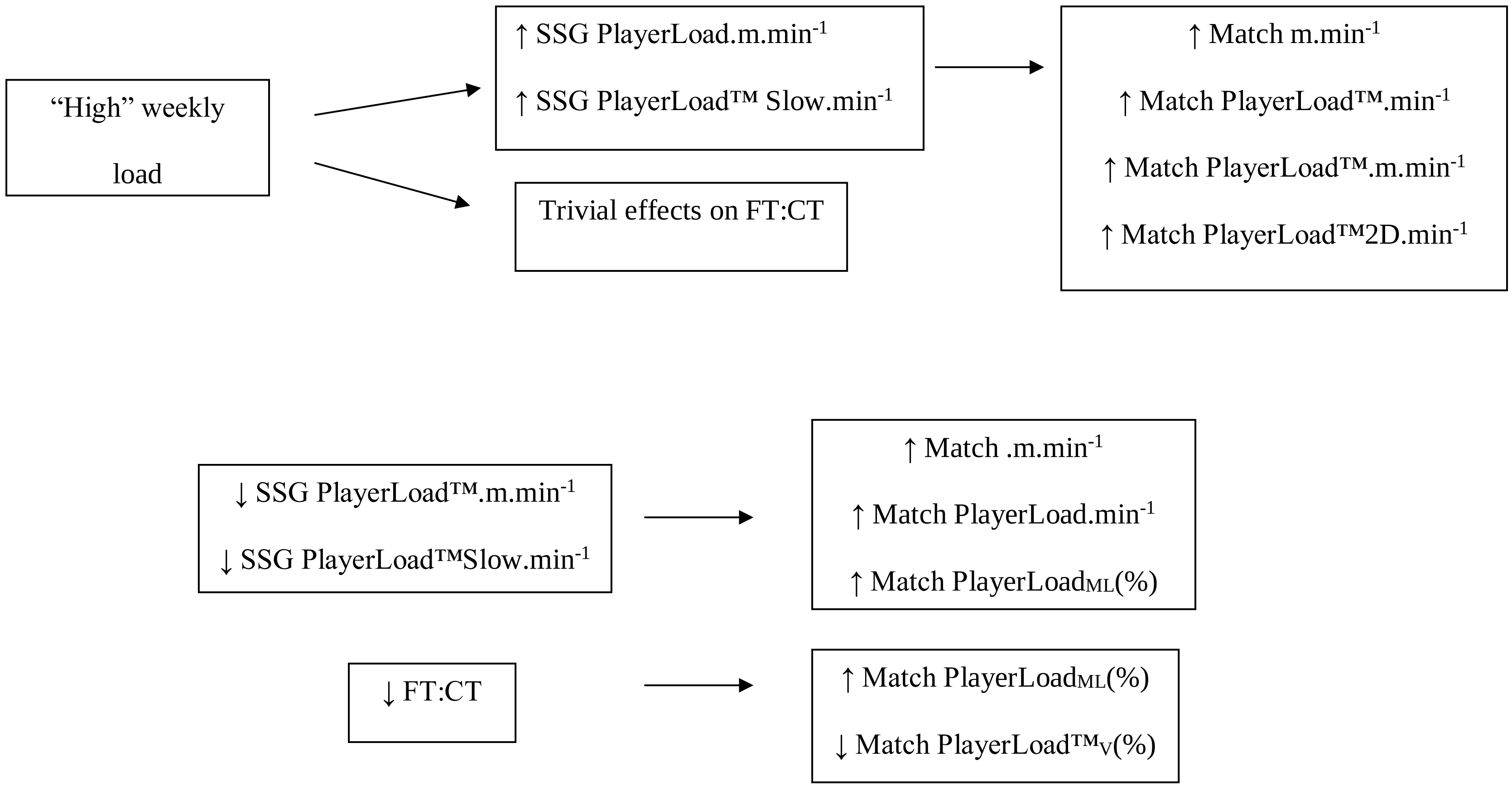

Figure 7.5 Diagrammatical representation of the impact of high weekly load on SSG accelerometer derived metrics and FT:CT, the related change in match activity profile due to increased SSG activity profile and the impact of suppressed SSG activity profile and FT: CT on subsequent match activity profile.

7.4 Discussion

The major finding of this study is that changes in accelerometer metrics reflecting an athlete's activity profile during a standardised SSG, performed on a weekly basis, was related to match exercise intensity via a change in movement strategy. The modifications in movement strategy during a match mirror the changes seen when FT:CT is suppressed. As a result, it appears that a standardised SSG is a useful tool for the assessment of neuromuscular fatigue.

7.4.1 SSG Reliability

The reliability of speed and distance variables assessed during the SSG in this study are similar to those reported by others (Hill-Haas et al., 2008b). A CV of 10% has been used as a threshold to declare a variable reliable (Jennings et al., 2010, Duthie et al., 2003). In the current study, $m.min^{-1}$ was well below this value and as a result appears to be a stable metric during a SSG. However, the high CV% of $HIR.min^{-1}$ suggests there may be limited scope for the use of this variable in examining SSG activity profile. Furthermore, the CV% of the accelerometer variables analysed in this study were comparable to those determined from treadmill running, Australian Rules Football training and match play, and rugby match play (Barrett et al., 2014, McLaren et al., 2016, Kempton et al., 2015, Boyd et al., 2013). Given PlayerLoad™ is likely to represent a more global measure of external load (Boyd et al., 2013, Barrett et al., 2014, Cormack et al., 2014) the results of this study suggest that PlayerLoad™ and its variants have the potential to be sensitive indicators of modifications in SSG activity profile.

7.4.2 Impact of Weekly Load on SSG Activity Profile & FT:CT

The first finding from this work is that relatively high preceding weekly training load results in an increase in accelerometer based metrics (i.e. PlayerLoad™.$m.min^{-1}$, PlayerLoad™Slow.min^{-1}) during a standardised SSG. These results are somewhat similar to the within-match changes in football players (Barrett et al., 2016a). In this work, the authors speculated that the increase in PlayerLoad™.m.min^{-1} seen late in the match was representative of decreased efficiency of movement due to match induced fatigue (Barrett et al., 2016a). In isolation, if an increase in PlayerLoad™.m.min^{-1} is in fact a reflection of a fatigue induced change in movement strategy, the results found here might suggest that a high weekly load has a similar fatigue effect on movement efficiency as brought about by match play. These changes may reflect a reduction in stride length, resulting in more frequent strides and foot contacts or movements at a lower velocity (Barrett et al., 2016a, Cormack et al., 2013). Critically however, the work of Barrett et. al. did not measure fatigue per se, to allow a comparison with the increase in PlayerLoad™.m.min^{-1} detected. The increase in PlayerLoad™.m.min^{-1} could in fact represent an increase in the amount of acceleration, deceleration and change of direction relative to distance covered (Dalen et al., 2016). This may be indicative of an "end spurt" resulting in an increase in activity profile rather than a manifestation of fatigue during the latter stages of the match (Bradley and Noakes, 2013, Paul et al., 2015). There is also the consideration of adjustments to changes in opponent tactical formation, that would influence match activity profile. Furthermore, the use of global PlayerLoad™ rather than the contribution of the individual vectors provides limited information on specific changes in movement strategy that might occur in fatigue (Dalen et al., 2016, Cormack et al., 2013, Mooney et al., 2013a).

Another potential explanation for the increase in PlayerLoad™.m.min^{-1} during the SSG seen following high weekly training load, could be that as players are aware they have a match to play the following day, they modify their SSG movements as a form of "pacing strategy" in response to perceived fatigue (Krustrup et al., 2002, Weston et al., 2011). Previous work has shown that perceived wellness impacts subsequent external training load and a similar mechanism may be at play here (Gallo et al., 2016). Despite these possibilities, an important factor with the current results suggests that "high" load weeks in this study are a sufficient stimulus to modify SSG activity profile. Although "high" load resulted in an increase in PlayerLoad™.m.min^{-1} and a metric that has previously reflected low velocity exertions; PlayerLoad™Slow.min^{-1} (McLaren et al., 2016), these modifications are in fact not manifestations of neuromuscular fatigue (see below for further discussion of this concept).

Whilst it was shown that a relatively high weekly load resulted in changes to SSG activity profile, the same load did not result in substantial changes to FT:CT. This variable has been demonstrated to provide an ecologically valid representation of neuromuscular fatigue in both Australian Rules Football and A-League Football (chapter 3) (Cormack et al., 2008a, Cormack et al., 2013). Importantly, this variable has displayed a dose-response relationship to match play in A-League players and an association with performance in Australian Rules Football players (Chapter 3) (Cormack et al., 2008b, Mooney et al., 2013a). Given these previous findings, it could reasonably be expected that if the players in this study were in fact in a state of neuromuscular fatigue due to high preceding load, that this variable would have detected it. Therefore, as players did not show meaningful reductions in FT:CT due to high training load, it appears that the changes seen in SSG activity profile due to high load may in fact not represent a negative (i.e. fatigue) response to previous training. This suggestion is supported by indicating a change in movement strategy (represented by a reduction in the contribution of the vertical vector to PlayerLoad™.min^{-1}) during Australian Rules Football matches when players were experiencing neuromuscular fatigue (Mooney et al., 2013a, Cormack et al., 2013). As mentioned above, although the increase in PlayerLoad™.m.min^{-1} has been suggested as indicative of match induced fatigue (Barrett et al., 2016a), the changes in accelerometer variables seen here may actually be a positive adaptive response to the previous high load (Aughey et al., 2016). Given the trivial changes seen here in FT:CT, it appears that the "high load" weeks as defined in this work were not a clear cause of neuromuscular fatigue. Furthermore, the ability in this study to assess changes in SSG activity profile changes in parallel to changes in FT:CT suggests that increases in PlayerLoad.m.min^{-1} during matches, previously proposed as representing fatigue (Barrett et al., 2016a), are questionable.

7.4.3 Impact of FT:CT on SSG activity profile

When FT:CT was reduced, there were concomitant reductions in PlayerLoad.min^{-1} and PlayerLoadSlow.min^{-1} during the SSG. As suggested, it appears that those weeks classified as "high" (relative to each players own season average) in the current study did not represent a sufficiently fatiguing stimulus to suppress FT:CT in isolation. This may be due to the fact that a preceding match has been shown to disturb this variable whereas training typically does not, presumably due to the lower volume and/or intensity of training sessions compared to matches (chapter 3)(Cormack et al., 2008a, Cormack et al., 2008b). Given that FT:CT typically recovers in A-League footballers by 42 hours post-match (Chapter 3), it appears that in this case, the timing of collection of FT:CT following the previous match, has meant that players have generally returned to baseline (Chapter 3). However, in situations where FT:CT remains suppressed, SSG activity profile on the same day as FT:CT has also been altered. This provides an indication that SSG activity profile is sensitive to neuromuscular fatigue. The changes seen are somewhat similar to the modifications to movement strategy seen during matches in Australian Rules Footballers who have a reduced FT:CT (Cormack et al., 2013), although the underlying mechanism responsible for these alterations is unable to be determined from the current data.

7.4.4 Impact of FT:CT on match intensity

Although the impact of preceding load on the changes in activity profile of a standardised SSG and FT:CT may be of interest, the key to the usefulness of a protocol as an ongoing monitoring tool lies in its ability to reflect changes in subsequent match exercise intensity and/or performance (Mooney et al., 2013a, Cormack et al., 2013). In other words, whilst a particular protocol may change relative to preceding load (i.e. match and/or training), if this change has no impact on exercise intensity, movement strategy, or performance within a match played in close proximity to the protocol, then the relevance of any changes seen are somewhat questionable. Similar to the impact on SSG activity profile seen with a reduced FT:CT, a suppression of FT:CT also elicited an alteration in match exercise intensity in the form of increased PlayerLoad™$_{ML}$(%) and lower PlayerLoad™$_{V}$(%). The reduction in the contribution of the vertical vector to PlayerLoad™ is identical to previous results in Australian Rules Football players that were classified as fatigued (Cormack et al., 2013). There are numerous potential mechanisms that might explain this finding. As suggested previously, reduced FT:CT might represent neuromuscular fatigue that directly limits the ability for high intensity movements and this may be related to a reduction in vertical stiffness (Cormack et al., 2013, Mooney et al., 2013a, Girard et al., 2011, Buchheit et al., 2015, Gaudino et al., 2013) . Alternatively, a reduction in FT:CT could result in an increased perception of effort required in order to produce a given external load, causing a reduction in high intensity movements (and resultant contribution of the vertical vector to total PlayerLoad™) (Cormack et al., 2013, Blanchfield et al., 2014). Furthermore, reductions in perceived wellness from a subjective questionnaire have been demonstrated to impact the relationship between perception of effort and external load measured via PlayerLoad and similar mechanisms may be involved here (Gallo et al., 2015).

7.4.5 Impact of SSG activity profile on match exercise intensity

Whilst the impact of reductions to FT:CT on subsequent match exercise intensity have previously been investigated (Mooney et al., 2013a) and also shown to be important in the current study, to our knowledge no study has examined the impact of changes in SSG activity profile (i.e. as a representation of neuromuscular fatigue) on match exercise intensity. In the current study, an increase in SSG PlayerLoad™.m.min^{-1} above baseline resulted in a reduction to PlayerLoad™$_{ML}$(%) and increase in PlayerLoad™$_{V}$(%) during a match. The increase in PlayerLoad™$_{V}$(%) during the match as result of elevated SSG PlayerLoad™.m.min^{-1} is opposite to the reduction in the contribution of the vertical vector to PlayerLoad™ that has been shown in Australian Rules Football players competing in a state of neuromuscular fatigue (Cormack et al., 2013). This adds further weight to the suggestion that an increase in PlayerLoad™.m.min^{-1} during the SSG (or other competitive situations) is in fact not a representation of a fatigued state.

In contrast, when SSG PlayerLoad™.m.min^{-1} and PlayerLoad™Slow.min^{-1} were lower than baseline, a similar pattern in match intensity to that of a reduced FT:CT was evident. That is, an increase in PlayerLoad™$_{ML}$(%) during the match and whilst unclear (suggesting individual variability) a potential reduction in PlayerLoad™$_{V}$(%). This finding provides additional support to the notion that “high load” as defined in this study does not represent a negative (i.e. fatiguing stimulus). The “high loads” in this study appear to be a positive stimulus and is similar to previous work suggesting improved match performance from relatively higher training load (Aughey et al., 2016, Gabbett, 2016a).

The results of this study suggest that reductions in specific SSG activity profile variables coincide with changes to match exercise intensity in the form of altered movement strategy. Specifically, the substantial reduction (greater than the %CV) in weekly SSG PlayerLoad™.m.min^{-1}, compared to baseline, resulted in a *likely* increase in match m.min^{-1}, PlayerLoad™.min^{-1} and PlayerLoad™$_{ML}$(%). Similarly a substantial reduction in weekly SSG PlayerLoad™Slow.min^{-1} compared to baseline displayed a *likely to very likely* increase in match PlayerLoad™$_{ML}$(%). Critically, the resultant changes in match exercise intensity are similar to those evident when FT:CT is reduced (i.e. *likely* increase in match PlayerLoad™$_{ML}$(%) also observed when reduced SSG PlayerLoad™.m.min^{-1} and PlayerLoad™Slow.min^{-1}). The reliability and ecological validity of FT:CT has previously been established (Chapter 3) (Cormack et al., 2008a, Cormack et al., 2008b), however the changes in match exercise intensity shown here add further weight to the value of this metric for assessing neuromuscular fatigue in field sport athletes. As mentioned previously, there are numerous potential mechanisms that may explain this outcome, although they are somewhat speculative as they have not been specifically measured in the current study (Girard et al., 2011, Cormack et al., 2013, Gaudino et al., 2013, Mooney et al., 2013a, Buchheit et al., 2015).

A novel outcome of this work is that accelerometer based metrics (PlayerLoad™.m.min^{-1} and PlayerLoad™Slow.min^{-1}) collected from the performance of a standardised SSG appear to be a useful surrogate for a test of neuromuscular fatigue such as FT:CT. Due to the time constraints and potential equipment limitations of performing a countermovement jump to assess FT:CT, coaches and practitioners may be able to determine similar information from a SSG performed as part of a warm up or during an on-field training session. Previous work has suggested the potential for the use of standardised protocols to collect heart rate recovery and heart rate variability data in the field (Buchheit et al., 2008, Buchheit et al., 2010b, Buchheit et al., 2012). Although potentially valuable, this approach is somewhat limited as heart rate data needs to be collected in a stand-alone protocol. The results of this study suggest that a standardised SSG may simultaneously be able to deliver physiological, technical, tactical and fatigue assessment outcomes. It should be acknowledged however, that a higher medio-lateral contribution to PlayerLoad™ has been observed when the accelerometer is placed at the centre of mass and higher vertical contribution when positioned at the scapula (Barrett et al., 2016b). As players in this study always wore units between the scapula in a custom tight fitting vest, the changes in vector contributions seen here are likely to represent meaningful modifications.

7.5 Conclusions and Practical Applications

From a practical perspective, reductions in PlayerLoad™.m.min^{-1} and PlayerLoad™Slow.min^{-1} during a standardised SSG appear to have the same implications for match exercise intensity (i.e. movement strategy) as reduction in FT:CT (i.e. increased contribution of PlayerLoad™$_{ML}$(%) to global PlayerLoad™). There is also the potential that given the individual variability shown here, that if PlayerLoad™Slow.min^{-1} is lower in a pre-match SSG compared to baseline, increased PlayerLoad™$_{V}$(%) may present in match play providing it is assessed on an individual level. Practitioners may consider the use of a regular standardised SSG for the assessment of neuromuscular fatigue. Future work should examine in more detail the impact of match performance in the presence of neuromuscular fatigue detected via a SSG.

CHAPTER 8. GENERAL DISCUSSION, CONCLUSIONS AND FUTURE RESEARCH

8.1 Introduction

The requirement of elite footballers to play at least weekly and commonly multiple matches per week, results in vital management and manipulation of load and recovery to improve performance. Due to the frequency of match play, there is limited opportunity for practitioners to expose athletes to sufficient intensified load to drive adaptation and maintain fitness across the season. The load-recovery relationship often results in a trade-off between the desire to improve performance and minimize injury risk. Performance improves when a positive adaptation – fitness outweighs the negative response of fatigue. Fatigue has positive stimulating effects and necessary for adaptation but can also have detrimental implications on performance both acutely and chronically if the correct balance is not achieved between load and recovery. Along with quantification of external and internal load, markers of fatigue for example neuromuscular, determined via CMJ and biochemical changes identified through cortisol and testosterone are common practice in elite sporting environments for athlete management to improve performance. However, given the commonality of monitoring load and recovery in team sports, somewhat surprisingly there is a lack of applied research identifying the impact of training and competition load on fatigue and recovery and match performance throughout a competitive season.

The global findings from this thesis and the practical implications include:

- The dose-response sensitivity of FT:CT determined from CMJ performance for detecting neuromuscular recovery following match play.

- The superiority of utilizing accelerometer derived metrics to quantify global external load in football and differences in neuromuscular recovery from different levels of accelerometer load.
- Internal load response variation across football playing positions and manipulating load exposure across the preceding 3 – 14 days to improve football match performance according to playing position.
- The benefits of a standardised SSG as a practical alternative to detect changes in movement associated with NMF.

8.2 The impact of match load on neuromuscular fatigue and hormonal response

Given the biggest contribution to load across the training week is match play, research has aimed to account for the dose-response relationship with the evaluation of external load commonly using GPS velocity based metrics (Weston, 2013). However, velocity metrics fail to account for changes in direction and body load occurring through GRF and contact with the ball or other players. Study 1 (Chapter 3) overcame the limitation of velocity metrics with the utilization of accelerometer derived PlayerLoad™ to quantify match load. Another key element that Study 1 identified was the difference between levels of dose (low, medium and high match load) on post-match recovery response. Utilization of markers of recovery is common practice in team sports, including NMF and hormonal response of cortisol and testosterone. The manifestation of fatigue can be extremely detrimental on athlete's performance and well-being if left undetected. Study 1 provided some crucial considerations when quantifying an athlete's neuromuscular recovery, that being actually accounting for differences in prior load exposure on the timing of response. Along with this Study 1 determined the most sensitive CMJ metric to accurately determine a change in performance in these elite footballers. Identifying the impact of prior load was achieved by the division of global accelerometer derived PlayerLoad™ into 3 levels (low: 0-500 au, medium: 500 – 1000 au and high: >1000 au). In accounting for the different levels of match load, Study 1 comprehensively identified the sensitivity of individual CMJ metrics. Study 1 provided support that increased exposure to match load, results in an impairment to neuromuscular function which appears to cause a reorganization of movement strategy to maintain the jump output of height. This was evidenced by a clear dose-response pattern observed with FT:CT to PlayerLoad™. Whilst research on CMJ performance had largely focused on reporting jump height and other outcome metrics (peak power and force) when the actual sensitivity to prior load was considered, FT:CT was far superior to jump height. It thus appears that the blunt outcome measures like jump height lack the ability to account for any underlying change in movement strategy, which can be detected by FT:CT (Gathercole et al., 2015b, Cormack et al., 2008c, Cormack et al., 2008a).

The implications of the results from Study 1 for detecting a change in neuromuscular performance in team sport athletes is their ability to re-organise movement strategy, which may result in limited change in jump height and a miss-interpretation of recovery status. The sensitivity in Study 1 of FT:CT justifies this metric being effective for the regular monitoring of neuromuscular recovery in football players.

To provide sufficient neuromuscular recovery following elite football match play, Study 1 identified 42 hours are required for an exposure to match derived PlayerLoad™ >500 au. The neuromuscular recovery of 42 hours is shorter than that of AFL players who require 72 hours (Cormack et al., 2008a) and likely to be the result of different load accumulation between sports. By accounting for the 3 different levels of

PlayerLoad™, Study 1 also identified that the low PlayerLoad™ (<500 au) group who were prescribed additional training the morning after the match, which is common practice for this group of footballers who are usually substitute players, had a different pattern of neuromuscular recovery. Suppressed FT:CT for low PlayerLoad™ presented at 42 hours, which is when medium and high PlayerLoad™ groups had appeared recovered. The different pattern of neuromuscular recovery is a consideration for practitioners to understand the impact of a "make-up" match load session and an expected reduction in performance of this group of athletes when main team training is re-introduced following match play.

In contrast to the dose-response relationship with FT:CT, the impact of various levels of match accumulated PlayerLoad™ on hormonal response was not as pronounced. A unanimous increase in cortisol and testosterone, with a decrease in T:C was observed post-match for all levels of PlayerLoad™, which suggests that any exposure to football match load results in a predominately catabolic response. By 18 hours post-match there was no clear impact of a change in hormonal response for any level of PlayerLoad™. Study 1 also identified that the re-introduction of training load following match play, resulted in substantial variability in the pattern of hormonal response to the various levels of PlayerLoad™. From a practical perspective, the substantial individual variability along with the expensive and time involved questions the utility of regular monitoring via hormonal analysis in elite footballers.

8.3 Effects of training and competition load on neuromuscular recovery, testosterone, cortisol and match performance during a season of professional football.

The goal of a successful training programme is to improve weekly match performance, via the manipulation of load and recovery. The demands of match-play, however, result in limited opportunity to expose football players to a training stimulus that promotes both physical conditioning and tactical development. As a result, team-based training is general practice. Although it is well established that individuals vary in their response to load, there had been no prior consideration for the impact of external training load prescribed to a football team, on the internal load responses of differing playing positions and importantly with a link to performance. It may be that a collective prescribed load leaves a positional group under exposed to their match demands, whilst another positional group exposed to the same training stimulus may exceed that required for successful match performance. This has implications for both under-and over-training, therefore impacting match performance. Whilst athletes can tolerate intensified load, a substantial spike above what the athlete is accustomed to leads to the biggest risk of subsequent injury. In an attempt to quantify a substantial increase in load, acute to chronic load has been compared using rolling averages. A rolling average is limited by assigning the same relevance to exposure to a load in an acute window to that in the chronic window, and therefore doesn't allow for the decaying nature of both fitness and fatigue over time. An alternative approach; the EWMA has the ability to account for load exposure having a differing impact, however prior to Study 2 (Chapter 5), this approach had not been applied to account for the impact of football training and competition load throughout a competitive season.

Whilst the results of Chapter 3 provided insight into the time course of recovery of neuromuscular fatigue and selected hormonal variables after match-play, it is unknown whether these responses impact performance in subsequent matches. The usefulness of these measures for ongoing monitoring purposes is somewhat dependant on their worth in predicting and protecting subsequent performance. Therefore, Chapter 5 explored the impact of internal load from training and match play on neuromuscular recovery, hormonal response and subsequent match performance throughout a competitive season, importantly relative to playing position.

The results of Study 2 revealed that different ratings of match performance were associated with changes in internal load relative to playing positions. Acknowledging a small sample size for each position for the defenders, increased internal load was met with a reduction in performance, whilst wide midfielders and forwards increased load improved performance. Another key finding from Study 2 was that the most influential windows of load exposure were more acute (i.e. 3 – 14 days) rather than the chronic exposure (28 days).

Considering the practical applications of the findings from Study 2, it would appear that a reduction in global internal load benefits the defenders in the two weeks prior to match play whilst wide midfielders and strikers benefit from an increased internal load. This may translate to adjusting training drills that promote a more attacking based outcome, or manipulating the internal load of defenders through either reduced minutes in match simulating drills where they have their biggest demand, or providing sufficient recovery from the impact of match play that may cause more psychological load. Overall, the results of Study 2 lend support to the importance of including internal load monitoring to account for positional differences in the response to external load performed as a team. However, it is also important to consider what external load has contributed to the internal load response as well as other factors including psychological wellbeing.

Study 2 also identified that a change in internal load was not associated with a substantial change in neuromuscular function identified through the FT:CT metric. However, the limited impact of a change in internal load on FT:CT may due to be a number of reasons. First, the measure of load in this study was internal, rather than external load. It appears that FT:CT may be sensitive to prior external load but not internal load. This may be because sRPE is impacted by psycho-biology rather than the physiological response in isolation (Borresen and Lambert, 2008b).

In contrast to the limited impact on FT:CT, a change in internal load was associated with an increase in both testosterone and cortisol and a reduced testosterone:cortisol, which was consistent across playing positions. However, the only association between hormonal response and improved performance, which is the key goal of the training process, was an increase in testosterone in the wide midfielders. Given the limited interaction between hormonal changes and subsequent match performance, coupled with the substantial individual variability of the hormonal response and the time and expense involved; the regular monitoring of hormonal variables was not conclusive from this work and is not recommended in the applied setting.

Overall, Study 2 contributes to the notion that improving performance cannot be a "one size fits all" approach. Whilst it is appealing to train as a team and achieve the target of rehearsing tactical patterns of play and match specific movements, this study identified that the response to load differs according to playing positions and this has an impact on subsequent performance. Monitoring processes therefore must consider this and the support of a global metric of internal load easily collected through RPE can prove greatly beneficial.

8.4 A standardised Small Sided Game Can Be Used to Monitor Neuromuscular Fatigue in A-League Football Players

The results from Study 2 identified that a change in internal load in a more acute period (3 – 14 days) had the biggest impact on subsequent performance. However, one of the areas that required further exploration from Study 2 was the impact of both external and internal training and competition load on NMF. Given also the limited interaction between internal load and a change in neuromuscular fatigue determined by FT:CT, Study 2 posed the question as to how external load would impact neuromuscular function and the impact this would have on subsequent match activity profile. The impact of neuromuscular fatigue on match movement patterns and rating of performance was identified via suppressed FT:CT (Mooney et al., 2013a, Cormack et al., 2013). However, given the additional costing of a force platform, it is not always an appropriate option to perform jump testing. Study 3 was developed with the desire to identify a monitoring tool that would be able to detect a change in movement associated with a state of fatigue to provide early detection while not interfering with the coaching of athletes. Studies 1 and 2 also identified the importance of monitoring metrics that not only have the ability to detect a dose-response relationship but are also cost-efficient, easy to implement, and reliable to administer.

During the competitive phase of the season, the weekly training regime is fairly consistent, with slight modifications based on days break, travel and quality of opposition. In an attempt to maintain and continue improving fitness throughout the season to peak at the end with finals, weekly load is often increased to achieve this. Whilst there has been prior concern on increased load and the risk of injury occurrence, an opposing view has also identified that team sport athlete's thrive with intensified load and have a better match performance when weekly load is increased from the prior week (Aughey et al., 2016). There is clearly a balance between intensified load to drive adaptation for improved fitness and performance, and too much that leads to fatigue and a risk of injury. Substantial interest is therefore placed on the impact of changes in load, and when intensified load starts to impact the athlete's movement and have a detrimental impact on performance.

It is common practice in team sport, and especially football to perform standardised training drills at consistent times throughout the training week. A prime example is

SSGs that promote match activity over confined spaces. Given the use of this drill to replicate match activity and that it is performed prior to match play, there was the consideration that a SSG may be able to be utilised to detect changes in activity profile that translates to changes in match activity. Prior to Study 3, there had been no exploration into the usefulness of a standardised training drill to provide not only a coaching stimulus but also useful for strength and conditioning and sports science practitioners to be able to utilise training drills to detect changes in movement pattern as a pre-cursor to match performance.

Study 3 identified that a “high” weekly load (determined by volume greater than an athlete’s individually calculated season average), resulted in substantial changes to accelerometer metrics during SSG drills. High weekly volume increased accelerometer derived PlayerLoad™.m.min^{-1} and PlayerLoad™Slow.min^{-1}. Whilst a relatively high weekly load resulted in changes to SSG activity profile, the same load did not result in substantial changes to FT:CT. Therefore, as players did not show meaningful reductions in FT:CT due to high training load, it appeared that the changes in SSG activity profile due to high load may in fact not represent a negative (i.e. fatigue) response to previous training.

Although an increased weekly training volume was not associated with causing a fatigue response, it was clear that when FT:CT was suppressed prior to match play, a change in match movement efficiency; increased contribution of the medio-lateral vector (PlayerLoad™$_{ML}$(%)) and reduction to the percent contribution of the vertical vector (PlayerLoad™$_{V}$(%)) was identified. This result mirrored that observed in elite AFL players (Cormack et al., 2013), which provides further support for the suggestion that reduction in FT:CT lead to alterations in movement strategy. Interestingly, a reduction in weekly SSG PlayerLoad™.m.min^{-1} and PlayerLoad™Slow.min^{-1} (>

%CV), resulted in a similar increase to PlayerLoad™$_{ML}$(%) during the match as evident when FT:CT was reduced. Increased PlayerLoad™$_{ML}$(%) during matches likely represents fatigue driven modification to movement strategy. As a result, it appears that a standardised SSG can be effective not only as a coaching drill but also as a practical assessment tool to detect NMF.

8.5 Conclusions

This thesis was aimed to develop a greater understanding into the interactions between training and competition load, recovery and match performance in elite footballers. This thesis revealed a number of novel insights that support the use of regular neuromuscular monitoring via FT:CT in professional football players along with quantification of external load via PlayerLoad™ in order to modify training load and maximise performance. Furthermore, changes in activity profile from a SSG can be used for detecting neuromuscular fatigue that manifest as modifications to movement strategy in matches.

The three research projects that formulated this PhD thesis were undertaken across multiple seasons with an elite football team. This provided several benefits as well as some limitations. Working within the football team, this PhD gave the opportunity for myself and my supervisors access to data from over 20 elite athletes and perform high level scientific research with this elite athletic population. Having the duel role of researcher and sports scientist at the club gave me the opportunity to relay the findings of my research directly back to the fitness, medical and coaching staff to inform and improve practices. Specifically, study 1 identified the rate of neuromuscular recovery following match play which dictated the timing of weekly CMJ testing at the club, with results used to inform and manipulate training load in the subsequent training days.

Studies 2 and 3 were performed across one competitive season, with the findings been used to influence the load exposure for the consecutive season. Importantly Study 2 identified differences in the response to training load relative to positional groups. This information was again crucial to inform the fitness and coaching staff of the ideal range of load exposure to be achieved in the crucial days leading in to match play per positional group. Given the ability to provide this feedback directly, and influence the existing practices at the club, the team achieved premiership and championship wins in the following season after data was collected and the findings used to directly influence load management. Whilst the hormonal analysis was limited in clear pattern of responses, the impact of neuromuscular fatigue was a big driving force in weekly monitoring and management at the club and also assisted with the club recording the lowest rate of injury across the A-League competition.

However, whilst the opportunity to conduct the research within an elite team provided a lot of clear benefits, there were also some challenges that I experienced. One of the biggest was the time constraints of research and the desire of elite teams to have instant feedback. Especially with the hormonal analysis which involved laboratory analysis, this feedback was delayed. Studies 2 and 3 also involved data analysis across the full season, and therefore the results could only be presented at the end of the season for use in the following season. There was also the limitation of a low sample size when data was split according to playing position (Study 2), and that the results of this PhD were specific to the players at one A-League team. Another limitation from a personal level was difficulty in time management and meeting the expectations of both the applied sports science role at the club and the PhD research. There was also the consideration that the research projects fit in to the training program at the club as well as being non-invasive to the athletes. Whilst this allowed for some very important information and feedback on the neuromuscular and hormonal response to training and match load, there were other elements that play a big role on recovery and performance that could not be identified in this thesis. Industry based PhD scholarships from my experience can be extremely beneficial for all involved. However requires a crucial understanding of the potential barriers to success and strategies in place to overcome these. Future Directions

Whilst this thesis has provided novel findings on the holistic monitoring of elite football players during a competitive season, future research on the interaction between training and competition load, neuromuscular recovery, hormonal response and match performance could explore the following:

- Collate match data across as many games as possible from a team to develop a reference point identifying athlete’s expected range of standard performance to be able to detect changes both weekly and across phases of the season.
- Utilise the collection of data from multiple matches to identify the time course of NMF during differing periods of the competitive season specific to playing positions as an alternate to global bands of PlayerLoad™.
- Applying the EWMA to recalculate daily external and internal load and identify the impact of differing accumulation windows and acute:chronic comparisons on NMF and movement patterns in training drills and match play.
- Integrating player performance statistics (such as passing efficiency) with accelerometer derived activity profile metrics to associate changes in movement efficiency with skill efficiency or decision making when fatigued in a match.
- Individualised monitoring of player’s weekly load to determine at what point load becomes intolerable leading to NMF and impacting match performance, and how this load is distributed across the training week. Also association of

weekly or fortnightly load on injury occurrence and the tipping point that causes a subsequent injury.

- Correlate wellness and psychological markers with external load to identify the contribution to internal load relative to playing positions to establish specific areas of load to manipulate and improve performance.
- Expand the studies to women's football, youth level football or different competitions to investigate differences in response between genders, age and competitions.

APPENDIX 1: STUDY 1 INFORMATION FOR PARTICIPANTS

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH

You are invited to participate in a research project entitled:

"The Time-Course of Neuromuscular Fatigue and Endocrine Response following an A-League Match"

This project is being conducted by student researcher Amber Rowell as part of a PhD study at Victoria University under the supervision of Dr Rob Aughey from the College of Sport and Exercise Science.

Project explanation

In elite sport, there is the balance between prescribing training and match induced loads, recovery and fatigue. When appropriate training is met with sufficient recovery periods, athletes will adapt to load, suffer minimal short-term fatigue and performance will improve. When periods of intensified training are coupled with insufficient recovery, prolonged fatigue occurs; resulting in the athlete being unable to maintain performance and the risk of sustaining an injury or illness is increased.

Muscular fatigue causes a reduced ability to generate maximal force. Following a match, declines in football performance have been found to last anywhere from 24 to 72 hours reflecting muscular fatigue. Monitoring levels of muscular fatigue experienced after a strenuous exercise bout such as a match is therefore important for establishing the extent of impact the match has and how long it takes post-match levels to return back to pre-match values. Performing a maximal counter-movement jump may provide a measure of the changes in force production following match play therefore assisting with player management.

A football match will also cause hormonal disturbances, in particular hormones Cortisol and Testosterone respond to stress on the body caused by exercise. Cortisol levels can increase 7 times higher than resting after both high-intensity and sub-maximal exercise. This demonstrates that an increased load such as that experienced during a match has an impact on the levels of these hormones. These hormones can be easily measured from a saliva sample and understanding their response to A-League Football may assist in designing effective individualised training programs.

To help understand the impact of training and competition on the fatigue response, it is important to measure what athletes have done (e.g. distance run) and how they feel. Tracking player movements throughout a match using Global Positioning System (GPS) technology provides a measure of the work athletes do throughout training and matches. A Rating of Perceived Exertion (RPE) scale can provide a measure of perceived physiological stress athletes experience during an exercise bout. Daily wellness questionnaires asking athletes to rate how they are feeling can also be used as a measure of how athletes are coping with training and may provide an early indicator of overtraining, fatigue, injury and illness.

This study will therefore determine:

1) The most useful variable obtained from a counter-movement jump as a measure of muscular fatigue status.
2) The time-course of muscular fatigue following A-League match play.
3) The time-course of hormonal response to an A-League match.
4) The relationship between the neuromuscular and hormonal response and player activity profile.

What will I be asked to do?

Countermovement Jump:
Firstly you will be asked to to complete a 2 minute warm up consisting of dynamic exercises and runs through an agility ladder positioned on the floor and then perform 3 practice jumps followed by 1 maximal effort jump. Jumps will be performed 24 hours pre-match, pre-match, post-match and 24 hours, 48 hours, 72 hours and 96 hours post-match.

Saliva Sample:
You will be asked to provide a saliva sample at the same scheduled time-point each day of testing (between 8:00 and 8:30am).
Prior to sample collection, please ensure you follow the listed protocols:

- Avoid alcohol for 24 hours prior to the sample being collected.
- Refrain from eating a major meal within 60 minutes of the collection time.
- Avoid dairy products 20 minutes prior to the sample.
- Avoid foods high in sugar, acidity and caffeine immediately before the sample.
- Only ingest water in the 60 minutes prior to the saliva sample being collected

Sample collection will require you to:

- Rinse the mouth with water 10 minutes prior to the sample being collected.
- Allow saliva to pool in the mouth.
- Tilt the head forward and passively drool into a collection cryovial until 1mL of saliva is gathered.

Samples will be collected 24hr pre-match, pre-match, post-match and 24hr, 48hr, 72hr and 96hr post-match.

Wearing a Global Positioning System (GPS) unit:
You will be asked to wear a GPS unit throughout the match. The unit sits in a pouch in an undergarment crop top to be worn underneath the playing top, where the GPS unit will sit securely on the upper portion of the back between the shoulder blades.

Wellness Monitoring:
Prior to the match you will be asked to complete a modified wellness questionnaire rating levels of muscle soreness and location, stress and fatigue and also any illness markers.

Rating of Perceived Exertion (RPE):
30 minutes post-match you will be presented with a rating of perceived exertion scale. You will be asked to give the number corresponding to the perception of effort for the match.

What will I gain from participating?

By participating in the study, you will gain exclusive feedback on the time-course of muscular fatigue and the response of Testosterone and Cortisol hormones to match induced loads. The study will provide you with the understanding of how the work you perform during the match impacts these two measures of fatigue which will assist with your monitoring and recovery for future matches. The information that this study will provide will also assist with the monitoring of your training schedule which could assist with preventing injury and/or illness.

How will the information I give be used?

Countermovement Jumps data will be analysed using computer software and statistical analysis. This information will be presented to coaching, fitness and medical staff at the club in an identifiable manner so that results may be used for adjusting individual and team match preparation and recovery.
Once saliva samples have been collected, they will be placed on ice and transported to Victoria University where they will be stored in a -80˚C freezer. Samples will be de-identified. Samples will be stored in the freezer until they are ready to be analysed. Samples will be analysed only for levels of bound Cortisol and Testosterone within the saliva. The samples will be stored for up to 12months. Once samples have been analysed, results of this data will be presented to coaching, fitness and medical staff at the club in an identifiable manner so that results may be used to adjust individual and team training and recovery.
Statistical analysis will be conducted with all data to establish the impact of an A-League match on the time-course of neuromuscular fatigue and endocrine response. Results will be presented to you and coaching staff informing of the findings. Results will then be de-identified and submitted to an academic journal where they will be made available to the general public to increase the knowledge on the impact an A-League match has on the time-course of neuromuscular fatigue and hormonal response.

What are the potential risks of participating in this project?

There are very limited potential risks associated with the project including:

- The possibility of sustaining an injury when performing the counter-movement jump on the force plate.
- The possibility of sustaining an injury throughout the match.
- The slight risk of being concerned with performing poorly in front of coaches/peers.

In the unlikely event of an injury occurring either when performing the maximal jump or during the match, the club physiotherapist, doctor and fitness staff will be on hand to provide immediate treatment.
Performing the maximal jump and providing the saliva sample will be in a separate room to the rest of the playing group to minimize the chance of feeling uncomfortable. Identifiable results will only be presented to coaching, medical and fitness staff within the club. When data is presented to the broader general public with the publication of results in a scientific journal, data will be de-identified and presented as a team average, eliminating the chance of individual players' data being identified. Should you feel you have any psychological issues concerned with the project, the details of a VU psychologist are listed below for your use:

Harriet Speed
Ph: (03) 9919 5412
Email: Harriet.Speed@vu.edu.au

You are also free to withdraw from the study at any time without this impacting your role and position within the team.

How will this project be conducted?

The single, maximal Counter-movement Jump and saliva samples will be performed and collected 24 hours pre-match, immediately pre-match, immediately post-match and 24 hours, 48 hours, 72 hours and 96 hours post-match. Wellness ratings will be collected before the match. GPS units will be worn throughout the match and RPE will be collected 30 minutes post-match.
Results obtained from the counter-movement jump will be analysed to determine what variable if any is the most sensitive measure accounting for changes in neuromuscular performance occurring as a result of on A-League match.
Performance in the counter-movement jump and hormonal markers collected post-match will be compared to the pre-match results to determine the magnitude of change occurring from the stress caused by match play. Variables collected from the GPS along with wellness and RPE ratings will be statistically assessed against the counter-movement jump performance and hormonal response to determine which match related variables are linked to the markers of fatigue.

Who is conducting the study?

The project is collaboration between the MVFC and Victoria University.

The Chief Investigator for the study is:
Dr Rob Aughey (PhD);
Senior Lecturer in Exercise and Sport Physiology, College of Sport & Exercise Science.
Senior Sports Scientist at the Western Bulldogs Football Club.
Phone: 61 3 9919 6329
Fax: 61 3 9919 4891
Email: robert.aughey@vu.edu.au

The Student Researcher is:
Amber Rowell
Phone: 0458 142 814
Email: ARowell@mvfc.com.au

Any queries about your participation in this project may be directed to the Chief Investigator listed above.
If you have any queries or complaints about the way you have been treated, you may contact the Ethics Secretary, Victoria University Human Research Ethics Committee, Office for Research, Victoria University, PO Box 14428, Melbourne, VIC, 8001 or phone (03) 9919 4781.

APPENDIX 2: STUDY 2 AND 3 INFORMATION FOR PARTICIPANTS

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH

You are invited to participate in a research project entitled:

"The Relationship between player fitness, fatigue, endocrine response, wellness, injury and performance throughout a competitive A-League football Season".

This project is being conducted by student researcher Amber Rowell as part of a PhD study at Victoria University under the supervision of Associate Professor Rob Aughey and Associate Professor Andrew Stewart from the College of Sport and Exercise Science and Dr Stuart Cormack from Australian Catholic University.

Project explanation

In elite sport, continual monitoring attempts to ensure there is an appropriate balance between the physical demands of continual training and match play, recovery and resultant fatigue to improve performance and minimise prolonged illness and injury. Changes to fatigue status, hormonal levels of cortisol and testosterone and player wellness has been linked to fatigue as a result of heightened periods of intensified training and match play in elite athletes. These factors may increase the risk of injury and prolonged illness if not managed effectively. Investigating the interactions between these measures throughout a season will provide an overall greater understanding as to how combined training sessions and match play impacts athletes' bodies which will ultimately lead to improved preparation and performance of individuals and the overall team. This project will investigate the interactions between training and match play, muscular fatigue and hormonal status, injury and wellness from existing data collected.

This project aims to investigate the relationships between player fitness, fatigue, hormonal responses, performance, injury and wellness over a competitive A-League football season. The application of a mathematical model to existing data collected as part of the monitoring practices will allow for the exploration of relationships between variables collected at an elite football club.

What will I be asked to do?

Allow the research team access to archival data collected as part of the regular monitoring practices at the Melbourne Victory Football Club. The information you will be asked to share is your countermovement jump testing results, levels of hormones Cortisol and Testosterone, daily wellness data, GPS data and medical data relating to the treatment and duration of any injury suffered. You will also be asked to allow the research team permission to use test results from VO2max, repeat and max sprint testing data.

What will I gain from participating?

By participating in the study and allowing the research team access to the data, you will gain exclusive feedback on the link between the impact training and match play has on your individual muscular fatigue response, Cortisol and Testosterone hormones, wellness and injury occurrence throughout a season and also the impact that your fitness levels and playing experience has on your individual response. This study will provide you, coaching, medical and fitness staff at the Melbourne Victory Football Club with a deeper understanding on how the work you perform during training sessions and matches impacts your muscular fatigue, hormonal levels of Cortisol and Testosterone, wellness and injury occurrence throughout a competitive season, This will ultimately assist with optimising recovery and preparation for future matches and hopefully minimise future injury occurrence.

How will the information I give be used?

By allowing the research team access to your data, a mathematical model will be developed using computer-based software for "data mining" purposes. This software allows exploratory and discovery research models to be developed 'ad hoc' as the researcher drills deeper into the data sets and various combinations of interactions arise. This approach will assist us to determine what interactions may be important (e.g. wellness data, counter- movement jumps data, hormonal data and injury occurrence throughout the season).
This data will be vital to report back to coaching, medical and fitness staff at the MVFC to assist with your recovery, maintenance and preparation leading in to and recovering from matches throughout a season. Results will then be de-identified and submitted to an academic journal where they will be made available to the broader scientific community to increase the knowledge on the impact of training and A-League match play on the time-course of muscular fatigue and hormonal response.

What are the potential risks of participating in this project?

There are very minimal risks associated with the study as it is utilising previously collected data to apply a mathematical model to determine interactions between training and match related variables, fatigue, hormonal levels, wellness and injury. Minimal risks of the study include:

1. Feeling pressured to allow the research team access to your individual data and taking part in the research.
2. Concerns that if you don't take part in the study this may hinder future selection in the squad.
3. Pressure to be involved in the study because teammates are.

You are under no obligation to be involved in the research project and the research project will in no way influence your availability for weekly team selection. The results of the study will not be used for comparison of athletes vying for team selection and you have the right to withdrawal from the study at any time. A psychologist is available to you, if you feel you wish to discuss any personal psychological issues arising from this study with:

Janet Young
Email: Janet.Yound@vu.edu.au

How will this project be conducted?

The research team will develop a custom mathematical model using computer software that will allow for the exploration into the impact of regular training and match play on muscular fatigue status, hormonal values of Cortisol and Testosterone, daily wellness and injury occurrence throughout a competitive season. The model will also determine the impact of individual fitness status and playing experience on muscular fatigue and hormonal responses, wellness and injury.

Who is conducting the study?

The project is a collaboration between the Melbourne Victory Football club and Victoria University. Amber Rowell, the sports scientist at the club and the student researcher will be the main contact for the study.

For further information regarding this study, please contact
Ms Amber Rowell
Phone: 0458 142 814
Email: arowell@mvfc.com.au

Investigators:
Associate Professor Robert Aughey – Chief Investigator
Associate Professor Andrew Stewart – Associate Investigator
Dr Stuart Cormack – Associate Investigator
Ms Amber Rowell – Student Investigator

Any queries about your participation in this project may be directed to the Chief Investigator listed above.
If you have any queries or complaints about the way you have been treated, you may contact the Ethics Secretary, Victoria University Human Research Ethics Committee, Office for Research, Victoria University, PO Box 14428, Melbourne, VIC, 8001 or phone (03) 9919 4781.

APPENDIX 3: STUDY 1 INFORMED CONSENT FORM

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

CONSENT FORM FOR PARTICIPANTS INVOLVED IN RESEARCH

INFORMATION TO PARTICIPANTS:

We would like to invite you to be a part of a study into determining the time-course of neuromuscular fatigue and endocrine response following an A-League match.
The Aims of the study are to determine:

1) The most useful variable obtained from a counter-movement jump as a field measure of neuromuscular fatigue status.
2) The time-course of neuromuscular fatigue following match play.
3) The time-course of Cortisol and Testosterone hormonal response to an A-League match.
4) The relationship between the neuromuscular and hormonal response and player activity profile.

The details of the project are fully outlined in the "Information to participants involved in research form" you have received with this form.

CERTIFICATION BY SUBJECT

I,
of:

certify that I am at least 18 years old and that I am voluntarily giving my consent to participate in the study:

"The time-course of Neuromuscular Fatigue and Endocrine Response following an A-League Match"

being conducted at Victoria University by: Dr Rob Aughey and student researcher Amber Rowell.

I certify that the objectives of the study, together with any risks and safeguards associated with the procedures listed hereunder to be carried out in the research, have been fully explained to me by: Amber Rowell and that I freely consent to participation involving the below mentioned procedures:

- Completing a modified wellness questionnaire prior to the match.
- Wearing a GPS unit throughout the match.
- Following set protocols associated with performing a maximal counter-movement jump 24 hours pre-match, pre-match, post-match and 24 hours, 48 hours, 72 hours and 96 hours post- match.
- I give my consent to provide a saliva sample to only be tested for Cortisol and Testosterone hormone levels 24 hours pre-match, pre-match, post-match and 24 hours, 48 hours, 72 hours and 96 hours post-match.
- Provide a rating of perceived exertion value 30 minutes post-match.

I certify that I have had the opportunity to have any questions answered and that I understand that I can withdraw from this study at any time and that this withdrawal will not jeopardise me in any way. I have been informed that the information I provide will be kept confidential.

Signed: Date:

Any queries about your participation in this project may be directed to the researcher: Dr Rob Aughey, ph. 9919 6329.
If you have any queries or complaints about the way you have been treated, you may contact the Ethics Secretary, Victoria University Human Research Ethics Committee, Office for Research, Victoria University, PO Box 14428, Melbourne, VIC, 8001 or phone (03) 9919 4781.

APPENDIX 4: STUDY 2 AND 3 INFORMED CONSENT FORM

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

CONSENT FORM FOR PARTICIPANTS INVOLVED IN RESEARCH

INFORMATION TO PARTICIPANTS:

We would like to invite you to be a part of a study determining the relationship between player fitness, fatigue, endocrine response, wellness, injury and performance in elite football players throughout a competitive A-League season.

This project will utilise existing data collected as part of the monitoring practices at Melbourne Victory Football club with the aims of investigating the relationships between player fitness, muscular fatigue, hormonal responses, performance, injury and wellness over a competitive A-League football season. The application of a mathematical model to the existing data will allow for the exploration of relationships between variables collected as part of the regular monitoring practices at an elite football club.

The details of the project are fully outlined in the *"Information to participants involved in research form"* you have received with this form.

CERTIFICATION BY SUBJECT

I,

of:

certify that I am at least 18 years old and that I am voluntarily giving my consent to participate in the study:

"The Relationship between player fitness, fatigue, endocrine response, wellness, injury and performance throughout a competitive A-League football season."

being conducted at Victoria University by: Associate Professor Rob Aughey, Associate Professor Andrew Stewart, Dr Stuart Cormack and Ms Amber Rowell.

I certify that the objectives of the study, together with any risks and safeguards associated with the procedures listed hereunder to be carried out in the research, have been fully explained to me by: Ms Amber Rowell and that I freely consent to participation involving the below mentioned procedures:

Allowing the research team access to the following data that has already been collected as part of the regular monitoring practices at the club:

- Daily Wellness.
- Jumps Testing Data.
- GPS Data.
- Hormonal Values of Cortisol and Testosterone only.
- Injury Data collected from the club physiotherapist Travis Maude, relating to the type, severity and duration of any injury suffered.
- Intermittent recovery test, VO2max, Repeat sprint and max sprint testing results.

I certify that I have had the opportunity to have any questions answered and that I understand that I can withdraw from this study at any time and that this withdrawal will not jeopardise me in any way. I have been informed that the information I provide will be kept confidential.

Signed: Date:

Any queries about your participation in this project may be directed to the researcher: Dr Rob Aughey, ph. 9919 6329.
If you have any queries or complaints about the way you have been treated, you may contact the Ethics Secretary, Victoria University Human Research Ethics Committee, Office for Research, Victoria University, PO Box 14428, Melbourne, VIC, 8001 or phone (03) 9919 4781.

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