Modelling training response, performance and injury risk in elite Australian football

by

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DOCTOR OF PHILOSOPHY

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ABSTRACT

Most team sports involve regular competition over the course of a season. There are several factors thought to affect match outcome in such a structured competition. These factors include days break between matches, match location, travel, team characteristics (age, height, and weight). All these factors can influence the structure of the training program. However, whilst monitoring training in an elite team sport environment is common practice, there are areas yet to be explored. The overall aim of this PhD thesis was to investigate factors affecting team success and the relationship between a global training load measure, match performance, and injury risk in an elite team sport. Three studies were undertaken to explore these ideas.

Study one quantified the effect of selected fixture and team-characteristics on match outcome for 5109 Australian football matches for 14 seasons. Selected factors included days-break between matches, location, travel-status, and differences between opposing team's age, body mass, and height. For every 10 matches played, the effects were: days break, 0.1 ±0.3 (90% CL) wins; playing away, 1.5 ±0.6 losses; travelling, 0.7 ±0.6 losses; and being in the oldest, heaviest, or shortest team, 1.9 ±0.4, 1.3 ±0.4 and 0.4 ±0.4 respectively. The effects of age and body mass differences were not reduced substantially when adjusted for each other.

A global training load was validated by quantifying the training-performance relationship in study two. The primary training load measure was weekly load derived from a weighted combination of Global Positioning System data and perceived wellness over a 24-week season. Smoothed and differential load were represented by an exponentially weighted moving average and rate of change in load respectively. Other derived training measures included monotony, strain, and acute:chronic ratio. Performance was generally highest near the mean or ~ 1 SD below the mean of each training measure, and 1 SD increases in the following measures produced small impairments: weekly load (defenders, forwards and midfielders); 1.5-week smoothed load (midfielders); 4-week differential load (defenders, forwards and midfielders); and acute:chronic ratio (defenders and forwards). The aim of study three was to assess training and match injury risk of elite Australian footballers, and the interaction between individual risk factors and derivative load measures. Weekly, smoothed and differential load, monotony, strain and

acute:chronic ratio was derived for each player across two consecutive seasons. Two variables for days since a previous injury (any and soft-tissue) and two measures of the percentage of pre-season completed (all and field sessions) and age of players were also recorded. Injury risk in matches was higher than training across all training measures and individual risk factors. The following measures produced substantial reductions in training injury risk: high weekly load, moderate to low 4-week differential load, moderate acute:chronic ratio, moderate smoothed acute:chronic ratio, very high percentage of pre-season completed (all). When examining match injury, a decrease in risk was associated with high weekly load, moderate 1.5-week smoothed load and high acute:chronic smoothed ratio.

This research encourages coaching and performance staff to consider fixture and team characteristics that can affect their chances of winning a match. The effect of days break and heavier teams challenge the current notion about balancing training with recovery and team selection. Periods of high acute load and sustained increases in load impaired match performance and positional differences should be considered for individual training prescription. Assessing match and training injury risk using a combination of external and internal load requires further investigation, although our findings indicate in-season training that features moderate load appears to be associated with the lowest risk. Maximising pre-season participation and monitoring a history of a previous injury may assist in protecting athletes against subsequent injury in training and matches.

STUDENT DECLARATION

I, Brendan H. Lazarus, declare that the PhD thesis entitled “Modelling training response, performance and injury risk in elite Australian 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: 28/6/2019

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ABBREVIATIONS

AFL	Australian Football League
AU	Arbitrary units
AU·min	Arbitrary units per minute
Cm	Centimetre
CV	Coefficient of variation
ES	Effect size
EWMA	Exponentially-weighted moving average
FFSTM	Fat-free soft tissue mass
FM	Fat mass
GAS	General Adaptation Syndrome
GPS	Global Positioning System
HID	High-intensity distance
HR	Heart rate
HRV	Heart rate variability
*HVR	High-velocity running
ICC	Intra-class coefficient
iTRIMP	Individualised training impulse
kg	Kilograms
$km \cdot h^{-1}$	Kilometres per hour
LSP	Local positioning system
MD	Mean difference
m	Meters
$m.min^{-1}$	Meters per minute
$m.s^{-1}$	Meters per second
$m.s^{-2}$	Meters per second squared

OR	Odds ratio
PL	PlayerLoad™
RPE	Ratings of perceived exertion
SD	Standard deviation
SE	Standard error
SEE	Standard estimate of error
SEM	Standard estimate of measurement
TEM	Typical error of measurement
TD	Total distance
TRIMP	Training impulse
UWB	Ultra-wideband
$\dot{V}O_2$	Maximal oxygen uptake
WASP	Wireless ad-hoc System for Positioning
Yo-Yo IRT	Yo-Yo Intermittent Recovery Test

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PUBLICATIONS

The following work has been presented at scientific meetings and/or published in peer reviewed journals in support of this thesis:

Publications:

1. **Lazarus, B.H.,** Hopkins, W.G., Stewart, A.M., Aughey, R.J. (2017). Factors affecting match outcome in elite Australian football: A 14-year analysis. *International Journal of Sports Physiology and Performance.*1-16 (Study 1, Chapter 3).
2. **Lazarus, B.H.,** Stewart, A.M., White, K.M., Rowell, A.E., Esmaeili, A., Hopkins, W.G. & Aughey, R.J. (2017). Proposal of a global training load measure predicting match performance in an elite team sport. *Frontiers in Physiology, 8* (Study 2, Chapter 4).
3. **Lazarus, B.H.,** Stewart, A.M., White, K.M., Rowell, A.E., Esmaeili, A., Hopkins, W.G. & Aughey, R.J. (2018). A holistic training load approach to assess soft-tissue injury risk in elite Australian footballers. *Currently being prepared for submission to Frontiers in Physiology* (Study 3, Chapter 5).
4. **Lazarus, B.H.,** Hopkins, W.G., Stewart, A.M., Aughey, R.J. (2015). Match success in elite Australian football: A 14-year analysis. Presented at the *8th World Congress on Science and Football, Copenhagen, Denmark.*

PUBLICATIONS ARISING DURING CANDIDATURE

The following work has been presented at scientific meetings and/or published in peer reviewed journals but are outside the scope of this thesis:

1. Aughey, R.J., Elias, G.P., Esmaeili, A., **Lazarus, B**, and Stewart, A.M. (2015). Does the recent internal load and strain on players affect match outcome in elite Australian football? *Journal of Science and Medicine in Sport,* 19:182-186.
2. Esmaeili, A., Stewart, A.M., Hopkins, W.G., Elias, G.P., **Lazarus, B.H.,** Rowell, A.E., & Aughey, R.J. (2017). Normal variability of weekly musculoskeletal screening scores and the influence of training load across an Australian Football League season. *Frontiers in Physiology, 9, 144.*
3. Esmaeili, A., Hopkins, W.G., Stewart, A.M., Elias, G.P., **Lazarus, B.H.,** & Aughey, R.J. (2018). The individual and combined effects of multiple factors on the risk of soft tissue non-contact injuries in elite team sport athletes. *Frontiers in physiology, 9*.
4. Rowell, A.E., Aughey, R.J., Hopkins, W.G., Esmaeili, A., **Lazarus, B.H.,** & Cormack, S.J. (2018). Effects of Training and Competition Load on Neuromuscular Recovery, Testosterone, Cortisol, and Match Performance During a Season of Professional Football. *Frontiers in physiology, 9.*

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CHAPTER 1. INTRODUCTION

Most elite team sports involve regular competition throughout a season. Team success may be defined as winning the league/competition, making the finals/play-offs, avoiding relegation, or finishing as high a ranking as possible. There are several factors, such as team and fixture characteristics and training load, that affect team and individual performance and subsequently has a large bearing on training periodisation and planning. Monitoring training load is important for assessing an athlete's training adaptation, fatigue, and recovery requirements, as well as minimising the risk of injury and illness (Halson, 2014).

Australian football is the most popular sport in Australia (Stewart, Nicholson, & Dickson, 2005). The goal of each team is to win as many games as possible, where the match outcome is determined by outscoring your opponent with 'goals' and 'behinds' worth six points and one point respectively. There are several factors related to the fixture and team characteristics that can potentially influence match outcomes. However, research has only investigated factors such as match location, days break, and travel in isolation (Clarke, 2005; Kelly & Coutts, 2007; Richmond et al., 2007) or characteristics (body mass, height, and weight) in only one cohort (Gastin, Fahrner, Meyer, Robinson, & Cook, 2013; Woodman & Pyke, 1991). To date, research investigating these factors utilising competition-wide data across multiple seasons does not exist.

Monitoring training has become the norm in elite sporting environments. Training load is the product of volume and intensity and can be quantified in terms of the work an athlete does (external load) and how the athlete responds to that load (internal load) (Halson, 2014). Training monitoring systems are well documented (Table 1 in Bourdon et al. (2017). Australian football generally involves external and internal load methods such as Global Positioning Systems (GPS; Aughey, 2011) and session ratings of perceived exertion respectively (Foster et al., 2001). However, in elite sport environments, monitoring systems tend to differ across professional teams rather than a universal approach. Performance staff select monitoring tools based on factors such as personal experience, their training program, and a cohort of athletes.

Literature has supported the use of a combination of external and internal load (Akubat, Barrett,

& Abt, 2014; Weaving, Marshall, Earle, Nevill, & Abt, 2014) rather than each measure in isolation, however, there is a lack of evidence using this approach in elite Australian football. Moreover, additional training measures can be derived to assist in the monitoring process. Training measures such as excessive accumulations or spikes in load calculated utilising session ratings of perceived exertion are documented in the literature (Williams, Trewartha, Cross, Kemp, & Stokes, 2016). However, it is unknown if such measures can be derived using a load measure like the one proposed in this study.

One of the key aims for performance staff is keeping their athlete's injury-free to avoid decrements in performance and overall success (Hägglund et al., 2013). Understanding the training load-injury relationship in elite sport is one key step in achieving this goal. Training periodisation requires careful management to elicit the stress required for positive training adaptation whilst providing adequate recovery. Performance staff utilise external and internal training load measures to examine injury risk in a team sport environment. Increased GPS parameters [e.g. very-high-velocity running (> 7 $m.s^{-1}$)] and session RPE substantially increase the risk of sustaining an injury (Gabbett, Jenkins, & Abernethy, 2012; Rogalski, Dawson, Heasman, & Gabbett, 2013). However, researchers have not used a combination of external and internal load measures to evaluate the load-injury relationship. Injury risk factors are generally recognised as intrinsic (internal to the athlete) and extrinsic (external to the athlete), which can be further subdivided into non-modifiable and modifiable factors (Bahr & Holme, 2003). Important factors that can modify the likelihood of sustaining an injury such as the amount of pre-season completed (modifiable), age (non-modifiable), and previous injury history (modifiable) (Murray, Gabbett, & Townshend, 2016; Rogalski et al., 2013) are identified in the literature. However, despite more recent attention, research investigating intrinsic and extrinsic factors in Australian football is limited.

This thesis will, therefore, evaluate the training response, performance, and injury risk in elite Australian football. The first study aimed to identify the effect of fixture and team characteristics on the chances of winning a match across 14 seasons. The second study focused on validating a global training load measure (a combination of external and internal load) by investigating the training-performance relationship relative to playing position. The third and final study used the same global training measure and derivative measures of load to assess training and match injury risk in one cohort. It should be noted that while the focus of this thesis is elite Australian football, comparisons from literature in other team sports are made where suitable.

CHAPTER 2. REVIEW OF LITERATURE

2.1 Australian football

Australian football is a contact team sport that involves intermittent periods of high-intensity activity (Johnston et al., 2012) that originated in Melbourne, Victoria in 1858. Today, Australian football is the most popular sport in Australia (Stewart, Nicholson, & Dickson, 2005) and is played throughout the country, including playing levels from junior to elite and involves elite men's and women's leagues. The elite men's competition is the Australian Football League (AFL), which currently has 18 teams. A season of elite Australian football has 23 competition rounds (one bye per team) followed by a finals series that includes four rounds. Each round of matches is generally played throughout a weekend (Friday to Sunday) between March and October. The last match of the season is the grand final where two teams compete for the premiership. The game is divided into four by 20-minute quarters plus stoppage time, interspersed by two six-minute quarter breaks and one 20-minute half-time break. Each quarter can include up to 10 extra minutes of stoppage time, which brings the total game time to around 120 minutes. Eighteen players from each side are allowed on the field at any one time and four players on the interchange bench that can be substituted or "rotated" at any time during the match (currently a maximum of 90 rotations allowed per team per match). The typical playing positions include six forwards, six midfielders, and six defenders and the game is played on an oval-shaped field that ranges from approximately 135 to 185 meters in length and 110 to 155 meters in width (Figure 2.1).

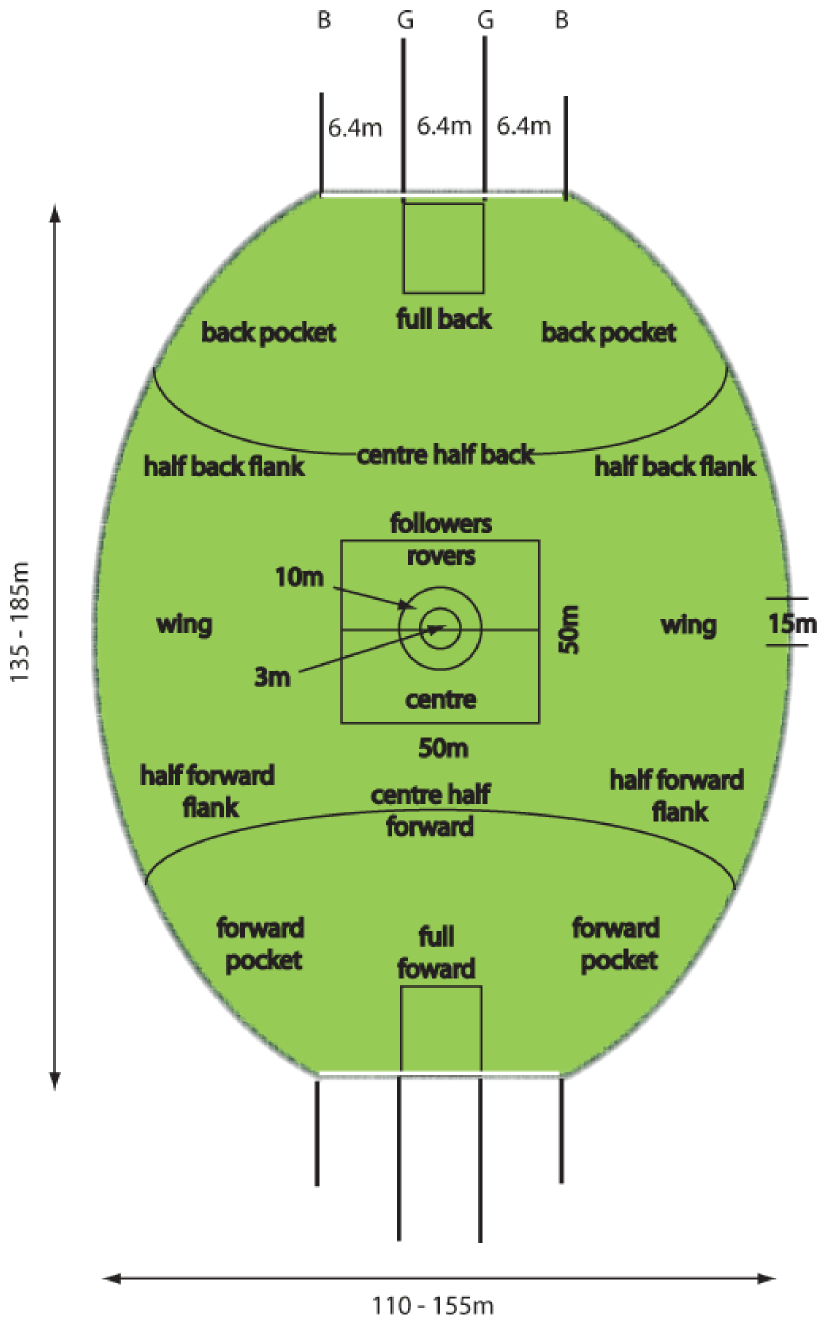

Figure 2.1. Australian football ground marked with dimensions and playing positions.

2.2 Factors affecting match outcome in team sport

The goal of every Australian football team is to win as many matches as possible, which in turn contributes to the team's ranking on the premiership table and ultimately the success of the team. Match outcome is determined by outscoring your opponent with "goals" and "behinds" worth six and one points respectively, as marked in Figure 2.1. Each win is worth four points, a draw two points, and a loss zero points towards the premiership table. There are several fixture and team characteristics that can potentially influence match outcome, but evidence for such effects is limited. The following sections will discuss these factors in a variety of team sports, including

Australian football.

2.2.1 Days break between matches

In Australian football, the fixtures consist of one match per round with the number of days break between matches generally between five to eight days. The introduction of two new teams (one in 2011 and one in 2012) created a "bye" round in the seasonal fixture, which increased the break between two successive rounds potentially up to 16 days.

The popular belief in Australian football is that the number of days break between matches impacts training periodization and performance (Buckland, 2015; Kelly & Coutts, 2007). For example, shorter breaks do not allow sufficient time to recover and prepare for the next match, whereas, longer breaks may lead coaches to include additional training to improve on facets of their game such as technical and tactical skill or physical fitness. There is some evidence to support the theory that shorter breaks between matches have a detrimental effect on subsequent performance, as it takes up to 72 hours for a key performance measure (countermovement jump) to return to pre-match level after an Australian football match (Cormack, Newton, & McGuigan, 2008). The response of a countermovement jump (flight:contraction time) was also observed across an entire Australian football season (Cormack, Newton, McGuigan, & Cormie, 2008). Athletes experienced substantially reduced neuromuscular status on 60% of data points throughout the season. It should be noted due to the nature of the Australian football schedule (matches potentially scheduled on different days over the weekend), there is difficulty in capturing data at the same time point every week therefore collection points varied throughout the season (72 to 120 hours post-match). Effective training periodization becomes very important to ensure players receive maximal recovery to compensate for maximal fatigue, particularly toward the end of the season (Cormack, Newton, McGuigan, et al., 2008). The appearance of creatine kinase in the blood is commonly reported in the literature as an indirect marker of muscle damage (McLellan, Lovell, & Gass, 2010). A similar time course to a countermovement jump response was identified when plasma creatine kinase concentration, a marker for muscle damage, took approximately 72 hours post rugby match to return to baseline levels (Takarada, 2003).

Days break between matches could influence individual player performance by limiting time for recovery from the previous match and physical and tactical preparation for the subsequent match. However, to the author's knowledge, only one study investigating days break and performance currently exists (Hiscock, Dawson, Heasman, & Peeling, 2012). In Australian football, following a 12-day break, players covered greater relative distance (137 ± 12 m.min^{-1}) and performed better (81 ± 0.28 AU.min^{-1}; playing impact ranking score) in comparison to a six-day (131 ± 12; 0.77 ± 0.33) an eight-day break (129 ± 13; 0.78 ± 0.27) respectively (Hiscock, Dawson, Heasman, & Peeling, 2012). The analysis was limited by including only two games (from one team) that were played after a 12-day break (Hiscock et al., 2012). It should also be noted that only one team that played 17 out of 22 games were included in the analysis. Analyses that include more teams from the competition and longitudinal research design (including multiple seasons) may provide more clarity into the effect of the number of days break on performance.

Recent literature has suggested the number of days break has no substantial influence on team success in team sports. The effect of recent internal load on match outcome in Australian football was investigated across six seasons (Aughey, Elias, Esmaeili, Lazarus, & Stewart, 2015). When days break was included as a covariate in the analysis, the weekly load was still higher for wins than losses [(effect size (ES) ± 90% confidence limits; 0.45 ± 0.27)] (Figure 2.2; (Aughey, Elias, Esmaeili, Lazarus, & Stewart, 2015). Authors indicated the number of days break between matches can dictate how much training is completed in a week (Aughey et al., 2015). However, given there is little time to recover from the last match to implement a new training stimulus, it may be relatively easy to periodise for smaller breaks between matches (Aughey et al., 2015). The influence of external factors on match difficulty was assessed in Super Rugby (Robertson & Joyce, 2015). Results identified a minimal contribution from days break in determining the difficulty of a match. Authors recommended ruling out the number of days break as a meaningful and negative impact on match outcome (Robertson & Joyce, 2015). Data collection over a season may cause the accumulation of other factors (such as playing away) to diminish the effects of days break. It may be beneficial to analyse days break over short intervals (i.e. monthly) and for coaches to positively communicate with players who believe they are disadvantaged from a shorter break.

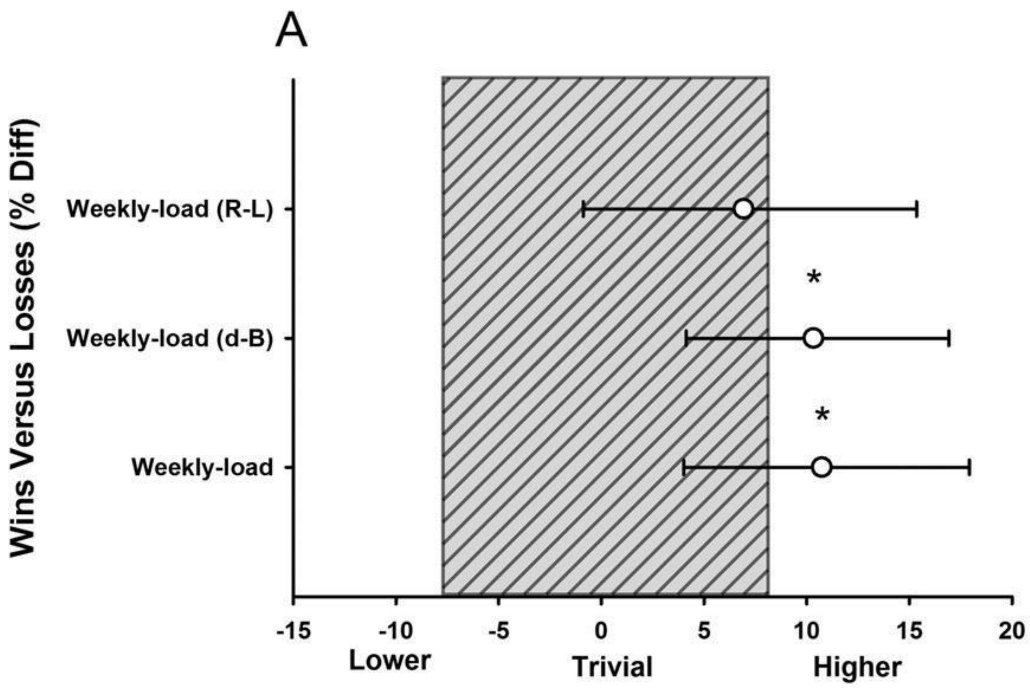

Figure 2.2. Percentage difference between wins and losses for weekly load, weekly load with covariates of days break between matches (d-B) and relative ladder position (R-L) from Aughey et al. (2015).

The AFL fixture differs from other elite team sports. For example, teams competing in the English Premier League (soccer) and National Basketball Association (basketball) play 38 and 82 matches during the regular season respectively, compared to 23 in the AFL. Further, soccer and basketball teams may be required to play two or three games in seven days whilst also completing training sessions. In contrast, Australian football teams generally play only one match in the same period and have one or two main training sessions per week (amongst recovery and strength sessions) depending on the number of days break. An example of the typical training week for an Australian football team can be seen below in Figure 2.3.

Time/Day	1	2	3	4	5	6	7
AM	Training or Recovery if match on Day 7	Off	Data collection & Flexibility	Individual skill training	Training	Recovery if no match PM	Recovery
PM	Weights	Off	Training	*Match* or Weights	*Match* or Off	*Match* or Off	*Match*

Figure 2.3. Weekly training and match schedule from an Australian football team (Cormack, Newton, McGuigan, et al., 2008).

The distinction between fixtures in team sport highlights the importance of balancing positive training adaptation with the negative consequences caused by training stress and fatigue. Performance staff needs to ensure enough time is provided for the negative effect of fatigue to subside between training (Banister, Good, Holman, & Hamilton, 1986) taking into consideration the number of days break between matches.

2.2.2 The match location and home advantage phenomenon in team sport

Home advantage is defined as the designated home team in sports competitions that win over 50% of the games played under a balanced home and away schedule (Courneya & Carron, 1992). Match location, playing home or away, is the first component in the framework of home advantage research (Carron, Loughhead, & Bray, 2005). Other components of the framework include match location factors, psychological and physiological states, behavioural states, and performance outcomes as shown in Figure 2.4 (Carron et al., 2005).

Home advantage is an important factor in determining the result of a match and is one of the most documented phenomena in team sports (Pollard, 2008). However, due to its complex nature and the number of potential contributing factors concerning team sport, the home advantage phenomenon remains intricate.

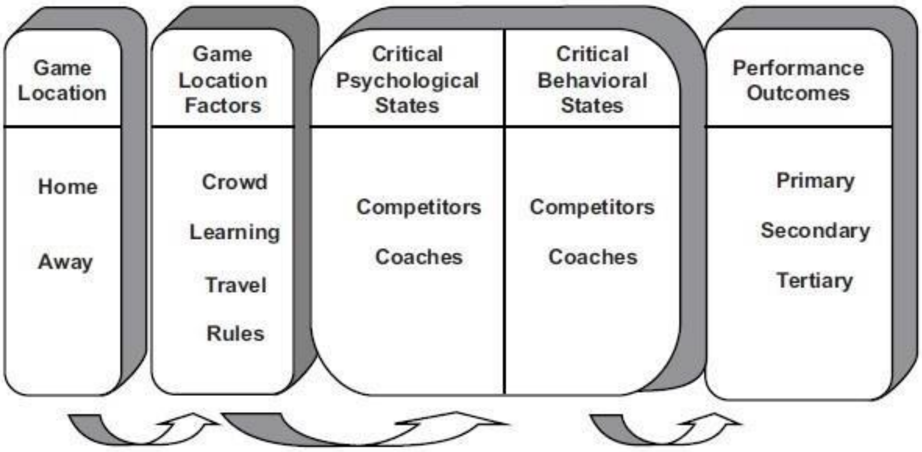

Figure 2.4. Framework for home advantage research (Carron et al., 2005).

Two longitudinal studies have investigated home advantage in soccer. The Fédération Internationale de Football Association (FIFA) is the governing body of world football (soccer) with 209 members each representing a different country or territory (Pollard & Gómez, 2014). First, home advantage was investigated in 157 national leagues across six seasons including a total of 169,752 matches (Pollard & Gómez, 2014). The home advantage for each confederation were as follows; Asia (n = 32; 56.9%), Africa (n = 38; 59.5%), North and Central America (n = 22; 57.9%), South America (n = 10; 62.5%) and Oceania (n = 5; 52.8%). A regression model was devised to describe the explanations of home advantage in this study including; FIFA ranking (a proxy for crowd support), geographical distance between teams, teams from a single city, teams at high altitude, the occurrence of civil war and corruption (Pollard & Gómez, 2014). However, the model accounted for only 43% of the variability in home advantage, which indicates other contributing factors have not been identified. Potential contributing factors such as crowd support and the referee may influence home advantage and will be discussed below. The home advantage (and consistency) of shirt colour in professional English soccer was investigated over 20 years (Allen & Jones, 2014). From 7720 matches, a home advantage effect was observed with 61% of total points accrued in home games and the advantage remaining consistent over time. Data reporting home advantage over the first 20 seasons of the Premier League has remained consistent over time (rho = 0.4). With regards to finishing ladder position, results reported teams, which finished lower on the league ladder, had a greater home advantage (rho = 0.28) compared to high ability teams. Team ability can influence the magnitude of home advantage and this has not declined in the modern era.

A home team generally receives stronger support through noise and reactions from the crowd, which tends to stimulate a player's effort and performance (Ponzo & Scoppa, 2014). The support from the crowd could lead officials to subconsciously favour the home team (Ponzo & Scoppa, 2014). Crowd effects (absolute size, density, divisional rivalry, and time of the year of the game) were examined in ice hockey (Agnew & Carron, 1994). Results indicated that only crowd density was related to match outcome (i.e. as the number of people in the crowd increased so did the home advantage). This finding is supported by work in soccer (Downward & Jones, 2007; Goumas, 2014). The number of yellow cards (a warning after committing a foul but still allowed to continue in the game; two yellows equal a red card and the player must exit the game) in 857 games played in the Football Association Cup was investigated across six seasons (Downward & Jones, 2007). A substantially greater number of yellow cards were awarded to the away team (n = 1465) compared to the home team (n = 1157; 23% difference or *small* effect). The effect of crowd size was interpreted in the following two ways: (1) crowd noise influences decision making of referees and (2) referees may aim to appease the crowd and are more likely to do so when crowd size increased (Downward & Jones, 2007). In Australian soccer, home advantage improved with increased crowd size over seven seasons, but only up to 20,000 people (Goumas, 2014). Home advantage (points gained, and goals scored) peaked at 66% but declined to 57% over the last three seasons. Australian soccer teams play a relatively small amount of games per season and attract much smaller crowds compared to European leagues, which may explain these findings (Goumas, 2014). Comparing absolute crowd numbers between leagues supports this. For example, across seven seasons of Australian soccer median crowd size was 9578, however, crowds in England across a similar timeline can draw up to 67000 people (Downward & Jones, 2007). Absolute crowd size was positively related to home advantage in English and Scottish soccer (Nevill, Newell, & Gale, 1996). Authors believed the home crowd either provoked away players into committing more fouls or influenced the referees into favouring the home team. Home teams in the English Premier League with the highest match attendance, had a higher winning percentage (64%), penalties scored (71%) and a smaller number of red cards (33%) when compared to playing away (Nevill et al., 1996). When asked about home advantage and match success, female collegiate basketball players indicated home crowd support as the most important factor in winning matches (Bray & Widmeyer, 2000).

There is evidence in team sport that crowd noise can influence referee decisions and subsequently favour the home team. Research was conducted to identify the effect of crowd noise on officiating in the English Premier League (Nevill, Balmer, & Williams, 2002). Forty qualified referees were assigned to a crowd noise group (n = 22) or a silent group (n = 18) and were asked to officiate forty-seven challenges/incidents through video playback in a controlled environment. Referees in the noise group called 16% fewer fouls against the home team compared with the silent group. Interestingly, in both conditions, the referees did not call more fouls on the away team, suggesting the presence of crowd noise appears to reduce the number of fouls on the home team rather than increasing the amount on the away team. The effect of crowd noise in soccer is supported by research involving Australian football (Mohr & Larsen, 1998). Analyses of 171 games, which controlled for score differential, found home teams received 10% more free kicks than the away team (ES = 0.43). Free kicks that favoured the home team were given in their defensive zone, therefore, rather than helping the home team score, they restricted the scoring opportunities for the away team. Greater home crowd support and noise apply more pressure onto the referee, leading to an increased likelihood of referee bias for the home team (Pollard, 2006).

The concept of familiarity in home advantage is interesting, however, it has received limited attention. Home advantage may exist for teams on fields with smaller or larger dimensions (Clarke & Norman, 1995; Pollard, 1986). In Australian football, most fields differ in width and length. For example, a comparison can be made between two fields such as Domain Stadium, formerly Subiaco Oval (175 x 122 m), and the Melbourne Cricket Ground (160 x 141 m). Despite the evident differences, there has been no investigation into the role of field dimensions in Australian football. Research conducted in English soccer observed pitches with different sizes (Dowie, 1982). Two teams with the smallest and two with the largest playing surface did not accrue substantially more points (66%) when playing at home compared to the rest of the league (65%). Further, teams with a stadium capacity of over 40,000 did not influence their ability to win at home when compared to the rest of the league (Dowie, 1982). The relationship between familiarity and home advantage for high-quality teams (home winning percentage >50% before relocating) and low-quality teams (home winning percentage <50% before relocating) was examined (Loughead, Carron, Bray, & Kim, 2003). Moving to a new facility improved the winning percentage of low-quality teams (+13%) but hindered the high-quality group (-12%). Future research should be conducted to provide more clarity in examining the role of familiarity in the home advantage phenomena.

The last component of the home advantage framework involves the psychological and behavioural states of athletes. Game location factors impact player psychological states which in turn influence match outcome (Thelwell, Greenlees, & Weston, 2009). Psychological states can include a player's anxiety and self-confidence before playing either home or away, however, findings in this area are mixed. In a study of professional soccer players, no differences in pre-game anxiety between home and away games were reported (Duffy & Hinwood, 1997). Similarly, there was no meaningful difference in pre-competition anxiety and self-confidence for 26 individual junior skiers (ES = 0.01 to 0.06) (Bray & Martin, 2003). Bray and Martin were one of the first to utilise repeated measures (analysing the same athlete's home performance vs the same athlete away performance) to examine home advantage. This approach differs from previous research that has analysed home advantage as a percentage against chance (i.e. 50%) (Courneya & Carron, 1992). This approach appears to suit team or group data but cannot investigate individual performance and warrants further research. On the contrary to the above, there is evidence highlighting a positive relationship between home advantage and psychological states. Findings from a study involving female hockey players reported substantially higher levels of self-confidence and lower cognitive and somatic anxiety before home games compared to when playing away ($n^2 > 0.5$; *large*) (Bray, Jones, & Owen, 2002). Rugby union players also reported higher self-confidence (ES = 0.80, *moderate*) and lower anxiety levels (ES = 0.47 to 0.56, *small*) in home games compared to when playing away (Terry, Walrond, & Carron, 1998).

State anxiety, self-confidence, and the effect of team ability were investigated in male and female basketballers (Thuot, Kavouras, & Kenefick, 1998). Initial analysis showed, irrespective of the level of opponent, players exuded significantly greater confidence levels for home games but observed no difference in state anxiety. However, irrespective of the level of opponent, the secondary analysis highlighted predominantly no substantial differences (ES = 0.12 to 4.66) for male and female player's self-confidence. Further, it is believed that more experienced individuals have better psychological skills/status compared to their inexperienced counterparts (Thelwell et al., 2009). Game location and experience on psychological status were investigated in soccer players with a success rate of 63% (home team won 10 out of 16 games) (Thelwell et al., 2009). A substantial interaction was found for game location and level of experience. Although speculative, players may utilise psychological skills such as relaxation, imagery, and self-talk more frequently at home, which may be harder to employ when playing away. The available research indicates sport type (e.g. individual or team) and game location may have an interactive effect on an athlete psychological state, therefore, even further investigation is required to fully understand this complex area.

Match location in elite Australian football can be considered the most unique of all Australian team sports. It is one of few team sports where the number of teams and the length of the season do not allow each team to play each other twice. As previously mentioned, the AFL involves 18 teams, ten of these teams reside in Victoria, and two teams are based in each of Western Australia, Sydney, Queensland, and Adelaide. Thirteen of the eighteen teams share home grounds; nine teams share two grounds in Melbourne, and two teams share grounds in each of Western Australia and Adelaide. In matches involving teams that have their stadia, there is a clear "home" and "away" team. However, in matches of teams in any given city where the ground is shared, the fixture designates the "home" and "away" team. In more recent years, AFL teams have commercial deals every season to transfer their "home" games to another stadium but are not full-time tenants of that stadium (e.g. Cairns, Darwin, and Tasmania).

Home advantage in Australian football was examined between 1980 and 1999 when the AFL involved only 16 teams (Clarke, 2005). In the 19 years analysed, 2299 (80%) of matches carried a home advantage. The teams with the home advantage won 1371.5 matches (half a point for a drawn match) or approximately 60%. This figure is consistent with other team sports, represented as mean home winning percentages and ES, including; baseball (54%, ES = 0.07), American football (57%, ES = 0.15), ice hockey (61%, ES = 0.22), basketball (64, ES = 0.29) and soccer (69%, ES = 0.38) (Courneya & Carron, 1992). In more recent times, the AFL has introduced two new teams and additional venues around Australia, which were not investigated in the previous study (Clarke, 2005). Therefore, it is likely the home advantage in the AFL has changed over the last 17 years.

2.2.3 The effect of travel on athletic performance

Elite athletes, particularly in team sports, experience sporadic air travel throughout the season and in some cases are required to cross multiple time zones. Air travel across time zones can cause decrements in athletic performance (Leatherwood & Dragoo, 2013). However, the effect of travel is multifaceted due to several different underlying factors with the potential to influence performance. The following section will discuss the effect of travel fatigue and jet- lag on team sport athletes.

Fatigue is generally defined as a state of weariness following mental or physical exertion and failure to maintain the required or expected work output (Edwars, 1983). Fatigue can be either central or peripheral. Central fatigue occurs when the central nervous system is no longer capable of responding to the output of the muscles (Taylor, Allen, Butler, & Gandevia, 2000). In contrast, when the muscles are incapable of producing the same output as they could at the beginning of exercise then peripheral fatigue has occurred (MacIntosh & Rassier, 2002). Travel fatigue is a combination of physiological, psychological, and environmental factors that occur during travel, accumulating over time reducing an athlete’s ability to recover and perform (Samuels, 2012). Symptoms of travel fatigue include lethargy, confusion, and headaches during and immediately after travelling (Waterhouse, Reilly, & Edwards, 2004). Several causes of travel fatigue in athletes include disruptions to routine (e.g. training, diet, and sleep), dehydration due to cabin air, and the process of travelling itself (Waterhouse et al., 2004).

Jet-lag refers to physiological alterations that synchronise the body clock and drive biological circadian rhythms due to air travel across multiple time zones (Leatherwood & Dragoo, 2013). The effects of jet-lag can appear after only crossing one time zone, however, effects are commonly associated with a minimum of three time zones crossed when symptoms are more prominent (Leatherwood & Dragoo, 2013). Symptoms of jet-lag include gastrointestinal disturbances, sleep disturbance, general fatigue, lapses in concentration, and mental performance (Leatherwood & Dragoo, 2013; Samuels, 2012). The length and severity of jet- lag symptoms are dependent on the number of time zones crossed and the direction of travel. For example, shorter recovery time is required following travel in a westward direction (Eastman & Burgess, 2009). It is known that symptoms of travel fatigue and jet-lag are detrimental to performance, however, there is a debate whether the symptoms affect team sport athletes.

Researchers have indicated deteriorations in performance for team sport athletes following travel across multiple time zones. The effect of travel on performance in the Australian Football League was assessed (Rowbottom & Pickering, 2000). Travelling across one to two time zones reduced the number of individual player kicks, marks and handballs, compared to matches at home (Rowbottom & Pickering, 2000). There was also a substantial difference in points difference for east to west (-25.4 ± 8.1 points) and north to south (-36.1 ± 10.4 points) travel. However, the effect of travel was not extrapolated by a two to three-hour time-zone shift indicating that the process of travelling was more detrimental than jet lag (Rowbottom & Pickering, 2000). It is important to note, only three seasons where both home and away matches between two teams during the same season were included, which limits the analyses and sample size. Similarly, to Australian football, an analysis conducted across six seasons of Australian national netball competition showed a decline in performance after travel across multiple time zones (Bishop, 2004). A *large* effect (ES = 1.0) was observed for points difference (home minus away margin) when comparing the local group (less than one hour) with the east to west (travel across two zones). One explanation could be home ground advantage, which is supported by the theory that as travel distance increases, the likelihood of there being a reasonable number of away fans decreases (Snyder & Purdy, 1985). On the other hand, given the *large* effect, it is likely the east to west travel played an important role in determining the number of points the home team would score.

The decline in Australian netball performance following travel is consistent with a study conducted in American football (Jehue, Street, & Huizenga, 1993). An overall reduction in winning percentage (-13%; day games and -24%; night games) was reported when teams from the National Football League travelled away from home. Interestingly, teams in a west time zone lost more games when playing against teams in a central (-16.7%) and east (-11.9%) time zone compared to other west teams (-6.2%) (Jehue et al., 1993). When comparing time zones, the number of games in a given analysis was small (West = 5, Central = 8 and East = 14). Although the analysis was conducted league-wide, a greater number of seasons may improve the statistical power of these findings. Strategies to alleviate the negative effects of travel, such as altering travel patterns and resettling in different time zones, could assist teams to mediate any expected decrement in performance, especially those to travel from west to east time zones.

There is evidence to support no substantial effect of short-haul air travel in elite Australian team sports. In rugby league players, the relationship between air travel and performance (tackles made, and metres gained) was assessed (McGuckin, Sinclair, Sealey, & Bowman, 2014). Results identified substantially more metres gained during home games (83.6 ± 49.1 vs. 63.0 ± 30.1 m; ES = ~0.5) and more tackles were made while playing away (18.4 ± 9.2 vs. 14.3 ± 6.7; ES = ~0.5). Short-haul travel resulted in symptoms of travel fatigue, however, did not negatively hinder individual performance. Given that short-haul travel provides only one piece of the puzzle, it is likely there are more underlying factors to consider when assessing rugby league performance. Factors such as opposing team tactics, player work rate, and ball possession are crucial key performance indicators that can influence subsequent team success (McGuckin et al., 2014). Elite soccer performance was analysed following short-haul travel (Fowler, Duffield, & Vaile, 2014). More competition points were accrued (ES = 1.10) and fewer goals were conceded (ES = 0.93) when playing home compared to away. Additionally, a *large* increase in shots on goal (ES = 1.2) and corners (ES = 1.5) was observed in home games compared to away. It seems premature to conclude that factors such as territoriality, tactics, and athlete psychological state have a greater impact on match outcome to air travel given data was only collected for six matches (affecting the power of this analysis). Travel fatigue, including crossing multiple time zones, may accumulate throughout a season, therefore a longitudinal analysis with bigger sample size is needed.

Research investigating travel and performance in Australian football is now outdated by not accounting for the recent growth in the number of teams and venues (Rowbottom & Pickering, 2000). It is likely the influence of interstate travel (which includes crossing up to three time zones) in Australian football has changed. Due to factors such as advances in technology and better resources, it is unclear whether the notion of the changing influence of travel on performance is a positive or negative one. Travel plays an integral part of the AFL fixture schedule; therefore, teams must understand the effect on match outcomes in the modern era.

2.2.4 The absolute and relative age effect in team sport

Any research involving athletes generally report descriptive statistics such as mean age and standard deviation (SD) of the variable of interest from the cohort. The inclusion of age is one factor to help understand the cohort being investigated. A concept that has received some attention is the relative age effect. The relative age effect is defined as the difference in age between individuals in the same age group (Musch & Grondin, 2001). The following section will discuss the absolute and relative age in team sports research.

Research involving age has mainly focused on team selection and describing player characteristics rather than investigating the effect of age itself. One study compared starters versus non-starters in a single elite Australian football team (Young et al., 2005). Starters (mean ± SD; 24 ± 3 years; 90 matches) were older and had more playing experience compared to non-starters (20.2 ± 2 years; 9 matches). Similarly, in semi-professional rugby, first-grade players were substantially older (25 ± 4 vs 22 ± 4 years) and had more playing experience (18 ± 6 vs 15 ± years) compared to the second-grade players (Gabbett, 2002). Players that make the starting line-up, who are generally the better players, are older than their teammates not in the initial playing cohort. Age and experience can be considered as linear variables, as experience can only increase with advancing age (Gastin et al., 2013). With the latter in mind, the older players are generally more skilful, hence their preference in team selection. Anthropometric characteristics were compared between fifty-four elite junior Australian footballers aiming to make the final squad of thirty-eight (Veale, Pearce, Koehn, & Carlson, 2008). In contrast to their senior counterparts, there was no difference between selected (16.7 ± 0.7 years) and non- selected players (16.8 ± 0.8 years) indicating age was not a factor in team selection. However, 65% of selected players were under the age of 17 compared to those not selected (50%). The same authors profiled elite senior and junior Australian footballers (Veale, Pearce, Buttifant, & Carlson, 2010). The mean and SD for the following groups were observed; junior (17.7 ±0.3 years), rookies (19.4 ± 0.7 years), and seniors (25.4 ± 3.9 years). As expected, senior players are *moderately* older than the elite juniors (ES = ~0.8) which indicates age should be taken into consideration when assessing the physical expectations of the athletes (Mujika et al., 2009; Veale et al., 2010). These results are useful for performance staff to design age-specific training programs for elite junior Australian football players (Keogh, 1999).

Literature considering the effect of age on team performance in team sport is sparse. One study investigated the influence of weekly training load on match performance including an evaluation of age and playing experience (Gastin et al., 2013). Player's age and playing experience were highly correlated ($r > 0.90$) and had a substantial impact accounting for 45% of the total variability in match performance data. The effect of age and experience can be attributed to skill level and athleticism; such that older players compensate for their declining physical fitness with greater technical and tactical skill levels (Mooney, Hunter, O'Brien, Berry, & Young, 2011), whereas, younger players make up for their lack of experience with greater athleticism (Gastin et al., 2013). The age and experience of players are of importance for player management; exposing younger players to elite competition may extend their careers by building resilience when physical characteristics and experience are improving. It should be acknowledged the possible repercussions of exposing younger athletes earlier in their careers such as injury.

A longitudinal analysis of the relative age effect in Australian football found a bias of selected players that were born earlier in the year (January to March) (Coutts, Kempton, & Vaeyens, 2014). The opposite was discovered for mature aged draftees, with a substantial bias towards players born in the latter part of the year (July to December). This finding can be related to mature aged players being physically and psychologically superior and exposed to a higher level of coaching. Similarly, the effect of relative age was investigated in youth soccer players (Kirkendall, 2014). Older players, generally taller and heavier, are thought to improve a team's chances of winning. A relative age effect was identified when comparing the first and fourth quarters of the year (29.6% vs 20.9% respectively). However, there was no systematic influence of team mean age on match outcome indicating that team selection should not be based on physical maturation alone.

2.2.5 Anthropometry and team sport research

Anthropometry is the measurement and proportion of the human body (Johnston, 1982). Studies that involve athletes generally report descriptive statistics of anthropometric variables such as height and body mass. Team sport athletes who are taller/shorter or heavier/lighter may have the potential to influence the outcome of a match, however, this notion has yet to be established in the literature.

Anthropometric characteristics are anecdotally important considerations for team selection in team sports, however, there is little evidence to supporting this notion. Anthropometric parameters of starters and non-starters in an elite Australian football club were compared (Young et al., 2005). Height, weight, and sum of skinfolds (mean ± SD) for starters and non- starters were; 1.86 ± 0.1 and 1.89 ± 0.1 m, 88.9 ± 8.6 and 85.9 ± 9.9 kg, 52 ± 16 and 52 ± 8 mm respectively. No overall differences were observed between the two groups, but in a comparison of positional groups (defenders, forwards, and midfielders) only the midfielders had substantially lower skinfolds than the forward group. All other anthropometric measures were unclear. The latter is consistent with no reported differences in height, body mass, and skinfolds when comparing elite under-18 and senior AFL players, despite the AFL players being fitter and stronger (Marchant & Austin, 1996).

Inevitably, older players will eventually be replaced in a team by their younger counterparts (Gabbett, 2002). To provide opportunities to gain experience, coaches should expose younger players to higher levels of sport (Gabbett, 2002); however, it is unknown whether they are ready to cope with the demands in their current physical state (Gabbett, 2002; Pyne, Gardner, Sheehan,

& Hopkins, 2005). In a junior Australian football cohort, selected and non-selected players were compared (Veale et al., 2008). Selected players were taller (182.6 ± 7.9 cm; ES = 0.51) and heavier (77.4 ± 10.3 kg; ES = 0.40) compared to non-selected players (178.7 ± 6.6 cm and 73.6 ± 8.6 kg respectively). Being taller and heavier supports research that advocates the importance of using anthropometric data to assist in the selection process (Pyne et al., 2005). Second, three AFL cohorts were compared to identify if junior players are mismatched with their senior counterparts (Veale et al., 2010). There was no clear difference between junior, AFL rookies, and AFL senior height (187.02 ± 8.1 cm, 188.1 ± 5.6 cm, and 187.4 ± 6.7 cm, respectively). When body mass and lean mass were compared, elite junior players were *moderately* lighter than both AFL cohorts (ES = 0.7). This finding can be expected based on physical maturity and longer exposure at the professional level of football. While individual maturation cannot be controlled, junior athlete's anthropometric characteristics should be regularly measured and monitored.

Performance staff is challenged to develop and maintain physical characteristics of team sport athletes throughout different phases of the season. One effective way of monitoring the efficacy of the training program is assessing changes in anthropometric attributes via dual-energy X-ray absorptiometry (DEXA). DEXA has assessed the body composition in a healthy population (Rothney et al., 2012) and is now widely accepted as the criterion method for assessing athletes (Sutton & Stewart, 2012). The accuracy of DEXA was tested on elite team sport athletes (Bilsborough et al., 2014). Test-retest reliability was derived from repeated scans in thirty-six professional players. DEXA showed excellent precision for bone mineral content (CV% = 0.6 to 1.5%) and fat-free soft tissue (CV% = 0.3 to 0.5%) and acceptable reliability for fat measures (CV% = 2.5 to 5.9%). The changes in anthropometric characteristics were assessed over a competitive season in rugby league players (Gabbett, 2005). Height, body mass, and skinfolds were evaluated across four phases of the season; off-season, pre-season, mid-season and end season. There were no substantial changes in height (mean decrease of 1 cm) and body mass (mean increase of 2 kg) across the season. Skinfolds (mean ± 95% confidence intervals) were lowest during the pre- and mid-season phases (84.7 [73.2 to 96.2] and 84.3 [71.2 to 97.4] respectively), however, increased toward the end of the season (93.4 [82.1 to 104.7]). In

Australian football, body mass, fat-free soft tissue mass (FFSTM), and fast mass were assessed using DEXA across different season phases (Bilsborough, Greenway, Livingston, Cordy, & Coutts, 2016) and playing levels (Bilsborough et al., 2015). Fat mass of players with more than four years' experience decreased from the beginning to the end of pre-season (9401 ± 2711 g to 7160 ± 1596 g; ES = ~1.0) but remained relatively constant throughout the competitive season (6918 ± 1689 g). Similarly, the percentage of FFTSM increased from 84.5 ± 2.6% to 86.7 ± 1.4% during the pre-season phase and maintained throughout the rest of the season. The changes in anthropometry (excluding height) can be partly explained by the response of the athletes to diet and the training program. Elite senior (87.6 ± 7.3 kg) and sub-elite senior (84.04 ± 9.4 kg) players were substantially heavier than the elite junior cohort (78.5 ± 8.1 kg, ES = ~ 0.4 to 1.1) (Bilsborough et al., 2015). Although there were *large* differences for elite senior players in absolute mass and FFSTM, the relative proportion of FFSTM was not different between playing levels, which indicate the elite players had a lower percentage of fat mass.

One key aim of performance staff during the pre-season phase is to increase player strength. The latter is supported by a *large* correlation (r = 0.37 to 0.40) between changes in upper-body strength performance and FFTSM% during pre-season (Bilsborough et al., 2016). In contrast, leading up to the competition phase, the overall training load is generally tapered to offset the upcoming increase in match load and accumulated fatigue (Buttifant, 2003).

2.3 Monitoring training

Monitoring training helps to determine whether an athlete is adapting to the training program, assess fatigue and recovery status and to minimise the risk of non-functional overreaching (fatigue lasting weeks to months), injury and illness (Halson, 2014). Monitoring training practices in elite sport were investigated by surveying high performance staff (n = 45) across multiple sports (Taylor, Chapman, Cronin, Newton, & Gill, 2012). Results indicated that 91% of staff implement some form of monitoring system. Load quantification, fatigue and recovery monitoring were the focus of 70% of the responses. Key aims of the systems included; monitor the effectiveness of the training program (27%), maintenance of performance (22%) and preventing overtraining (20%). Monitoring systems are crucial for practitioners to understand how the athlete is coping with the demands of training and competition to ultimately improve performance (Taylor et al., 2012).

2.3.1 Theories of training

The first scientifically based explanation of improving fitness was portrayed by Yakovlev (1955). He proposed the supercompensation cycle that can be seen in Figure 2.5. The supercompensation is modelled around the interaction between load and recovery. The cycle is induced by a physical load (first phase), which causes the athlete to fatigue. The second phase, marked by fatigue, begins the recovery process, which improves the athlete's ability to perform another load stimulus. During the third phase, the athlete's work capacity increases further surpassing the previous level (supercompensation phase). In 1956, Hans Selye described this process as the General Adaptation Syndrome (GAS), where a stimulus results in a sequence of responses (discussed in Section 2.3.2).

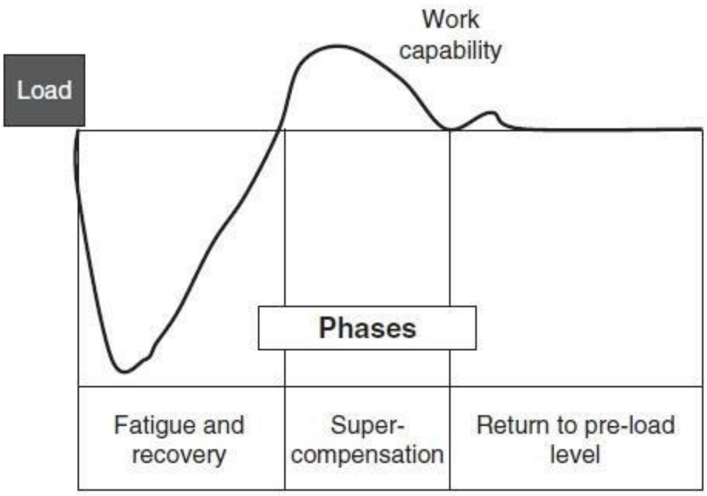

Figure 2.5. The supercompensation cycle following a single load (Yakovlev, 1955).

An expansion upon this theory was the Fitness-Fatigue model. Banister and colleagues (1975) proposed that performance could be defined as a 'fitness impulse' (positive response) and 'fatigue impulse' (negative response) from the training model such that; performance = fitness – fatigue (Figure 2.6). Both fatigue and fitness variables exponentially decline at different rates over time. It should be noted the influence of a training stimulus on fatigue is substantially larger than to fitness, however, the time decay of fitness is longer. If adequate recovery is provided to mediate the negative effects of fatigue between training, cumulative positive fitness responses of training will lead to improved physical capacity and performance (Bompa & Haff, 1999). There have been various adaptations to the Fitness-Fatigue model to account for the variation in training stimulus and accumulated fatigue (Busso, 2003; Calvert, Banister, Savage, & Bach, 1976; Fitz-Clarke, Morton, & Banister, 1991). Essentially, each model agrees that training impulse can elicit fitness responses (improve performance) and induce fatigue (decreased performance).

In elite sport, there are challenges for performance staff including but not limited to; facilitating decisions, utilising the available resources and finding a balance between practical and scientific information. Therefore, practitioners are encouraged to select monitoring parameters that suit their specific aims and training program (Bourdon et al., 2017). Research in the area of monitoring training in elite sport is extensive, however, much of these data remain confidential and/or unpublished (Halson, 2014). There is evidence that exists highlight a dose-response relationship between training load and several crucial aspects of team sport. These factors include and will be discussed in detail later in this literature review; injury risk (Section 2.4.3) and performance (Section 2.3.3.6). This section of the literature review will provide an overview of monitoring training load in team sport.

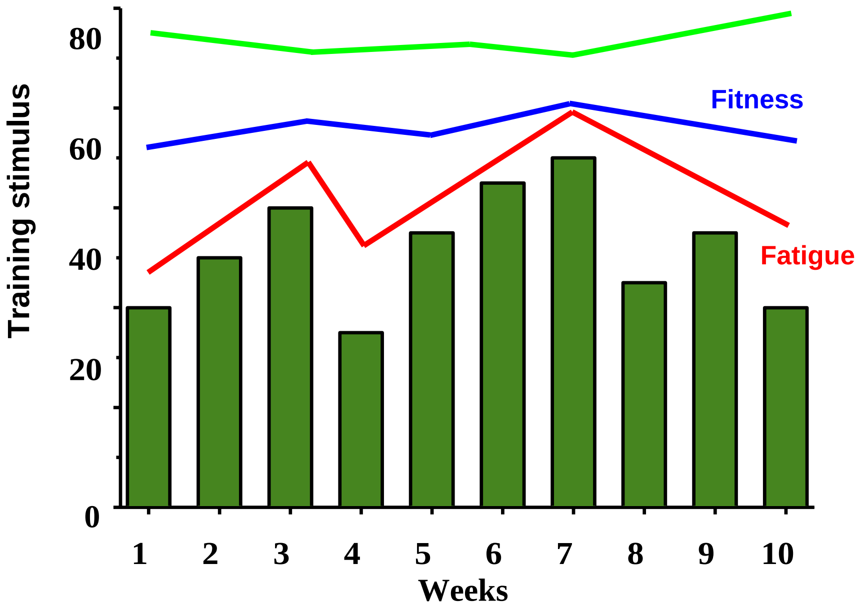

Figure 2.6. A model for predicting performance, where performance = fitness – fatigue, modified from Banister et al (1986).

2.3.2 Training periodisation in team sport athletes

The theory of periodization was first proposed for coaches and students, which divided the entire preparation phase into separate periods (Gorinevsky, 1927). The root of modern sports periodization is based on the GAS as mentioned in Section 2.3.1 (Selye, 1946). The GAS model refers to the adaptation process the body goes through when placed under stress and consists of three specific stages (Selye, 1946). The "alarm reaction stage" is the initial symptoms the body experiences under stress, which leads to the physiological response to deal with that stress. In the "resistance stage", the body begins to repair itself or build resistance to the stress experienced in the previous stage. However, the continuation of stress for extended periods can lead to failure of the body's adaptation mechanisms causing "exhaustion" (Selye, 1946). The basis of training periodization is aimed at maximising the stress incurred by training, correctly timed, whilst allowing adequate recovery. If achieved correctly, the exhaustion stage won't occur, the body can recover and ultimately improve performance. Training periodization was further developed into a seasonal program divided into smaller periods and training cycles as shown below in Table 2.2.1 (Bompa & Haff, 1999; Matveyev, 1964).

Table 2.2.1. A description of the training periodization cycles content and duration.

Preparation phase and duration	Content
Seasonal preparation (years)	Systematic athletic training planned over two to four-year cycles.
Macrocycle (months)	Large training cycle (usually an annual cycle) that includes preparatory, competition and transition periods.
Mesocycle (weeks)	Medium cycle that includes several microcycles.
Microcycle (days)	Small training cycle consisting of several days (usually a week).
Workout (minutes)	A single training session performed by an individual or group.

However, several limitations forced a revision of training periodization, particularly for elite athletes. Firstly, athletes lack enough energy supply to maintain performance with different load from various exercise modes over extended periods (Booth & Baldwin, 1996). For example, endurance training can elicit a few metabolic changes, whereas, heavy resistance training stimulates protein synthesis concerning muscle hypertrophy and maximal force output (Coffey & Hawley, 2007). Many sports require a combination of strength and aerobic fitness to perform in competition (Reilly, Morris, & Whyte, 2009). Training prescription and periodization becomes especially crucial to avoid any negative responses to concurrent training (Reilly et al., 2009). Different exercise modalities often influence training adaptations (Bell, Syrotuik, Martin, Burnham, & Quinney, 2000) and if insufficient recovery is provided athletes cannot recuperate (Bahr & Maehlum, 1986).

It is widely accepted the application of training periodization in team sport is different from other sports. Models of periodization for individual sports are generally based on athletes working towards peaking for a major competition or event in the season (Bompa & Haff, 1999; Matveyev, 1964). In team sports, such as Australian football, the competitive season takes place over several months requiring players to be prepared for multiple matches across the season. Hence, periodization techniques used for individual sports may be counterproductive for most team sports (Baker, 1998; Hoffman & Kang, 2003), causing reductions in lean body mass

(Allerheiligen, 2003), maximal strength (Astorino, Tam, Rietschel, Johnson, & Freedman, 2004), anaerobic power (Häkkinen, 1993) and maximal speed (Kraemer et al., 2004). Specifically, for team sport athletes, periodised training aims to develop and improve strength, power, body composition, fitness and ultimately performance. The annual training cycle differs throughout the relevant phases of the season in terms of duration, key training goals and training load (Figure 2.7). It is important to note, due to differences in sports, competition fixtures and training requirements, this schematic figure is only a guide. In team sports, like Australian football and rugby league, sport-specific terms are used such as off-season, pre-season and in-season (Baker, 2001; Gamble, 2006).

Overall, there is a strong case to adopt a methodical approach to monitoring training across the multiple phases in field-based team sports. Monitoring training can aid and guide practitioners with short- and long-term training prescription, and if training is prescribed correctly, lead to improvements in performance for athletes.

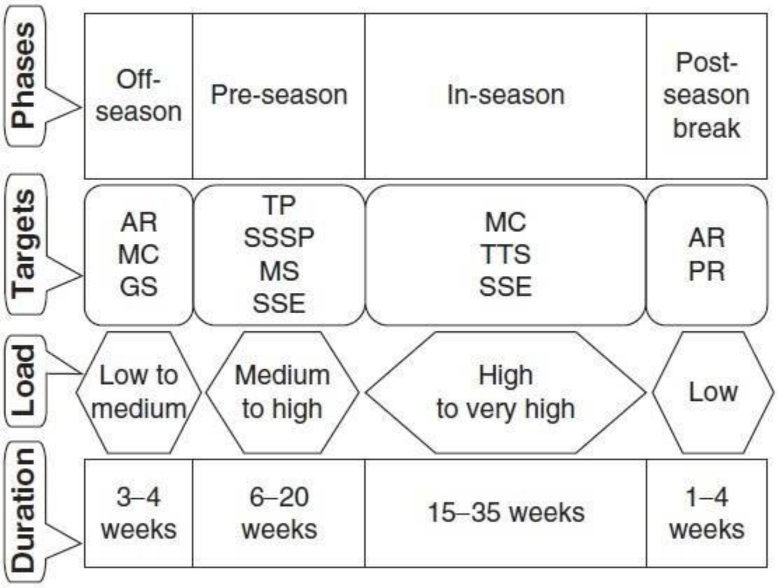

Figure 2.7. Annual periodization chart in team sports adopted from Issurin (2010). AR = active recovery; GS = general strength; MC = metabolic conditioning; MS = maximal speed; PR = psychological recovery; SSE = sport-specific endurance; SSSP = sport-specific strength/power; TP = technique perfection; TTS = technical/tactical skills.

2.3.3 Quantifying training load

Training load is a function of volume, intensity and type of physical activity performed during training and competition (Halson, 2014; Smith & Norris, 2002; Viru & Viru, 2000). The activity of an athlete can be considered in terms of what an athlete does (external load) and how the athlete responds to the given load (internal load) (Halson, 2014). Individual characteristics such as age, playing experience, injury history and physical capacity, combine with the external and internal load to determine the training outcome (Impellizzeri, Rampinini, & Marcora, 2005). For example, athletes completing the same session with identical external load could elicit different training responses (i.e. increased heart rate and perceived exertion) depending on the level of fatigue, recent training history or illness. Therefore, the training stimulus may be appropriate for one athlete, but too high or too low for the other (Gabbett, 2016). It is crucial to understand individual athlete responses to effectively monitor and manage load. There are various training load measures available to assist in monitoring practices and each elite sporting club generally implements their system. However, to date, there is little research investigating a load monitoring system that includes a combination of external and internal parameters (Section 2.3.3.9).

2.3.3.1 Quantifying external load in team sports

External load is defined as the work completed by the athlete measured independently of their internal characteristics (Impellizzeri et al., 2005; Wallace, Slattery, & Coutts, 2009). External load is commonly quantified by capturing athlete movement through tracking technologies such as vision-based systems, GPS and local positioning systems (LPS). Global positioning system technologies measure an athlete's position relative to the longitude and latitude coordinates of the playing area. This process can then be used to quantify an athlete's activity profile. For example, measures such as total distance, relative distance, speed and accelerations/decelerations are regularly reported in the literature (Cummins, Orr, O'Connor, & West, 2013; Dobson & Keogh, 2007). The quantification of external load using tracking technologies has become the norm in field-based team sports (Aughey, 2011; Cummins et al., 2013). Current GPS technology comes integrated with a tri-axial accelerometer. Tri-axial accelerometers used in isolation enable practitioners to capture information regarding physical contacts, collisions and sum of accelerations (Boyd, Ball, & Aughey, 2013; Cummins et al., 2013). The following section will discuss: 1) Athlete tracking technologies such as vision-based tracking systems, LPS, GPS and tri-axial accelerometers, 2) the validity and reliability of athlete tracking technology and 3) the quantification of external load using GPS and tri-axial accelerometer technology and the relationship to performance in team sport.

2.3.3.2 Validity and reliability of athlete tracking technology

Validity is the ability of equipment to produce the information what it is designed to measure (Atkinson & Nevill, 1998). There are two main different types of validity regarding athlete tracking technology. Concurrent validity is one measure assessed against a criterion measure or gold standard. Convergent validity examines two measures that are designed to measure the same construct to show they are related. Several measures are used when validating athlete tracking technologies such as pre-defined courses, infra-red timing gates (in conjunction with pre-defined courses), laser devices and three-dimensional motion analysis (Vicon). Reliability assesses the precision or consistency of measures provided by tests, items of equipment or operators of the equipment (Atkinson & Nevill, 1998). The most common form of reliability is retest reliability, which refers to the consistency of values when measuring the same subjects twice or more over a period. The statistical analysis used to describe the measures discussed above can vary. The standard estimate of error (SEE), standard error of measurement (SEM), coefficient of variation (CV) or percentage difference from the criterion measure are commonly used. Reliability is calculated over repeated trials and commonly presented as a coefficient of variance (CV), typical error of measurement (TEM) or intra-class coefficient (ICC). The following sections will discuss the validity and reliability of each athlete tracking systems that are currently utilised in elite team sport environments.

2.3.3.3 Automated vision-based tracking systems

Automated vision-based tracking systems were designed to monitor athlete activity profiles without the need for a human camera operator. Vision-based systems are comprised of multiple, fixed cameras positioned around a designated training or playing area. To improve accuracy the designated area should be covered by a minimum of two cameras (Di Salvo, Adam, Barry, & Marco, 2006). Post-training or match information from each camera is automatically synced to one dataset. Athlete position is determined relative to the designated area and the continuous trajectories of the athlete are then predicted (Di Salvo et al., 2006). The following section will briefly discuss vision-based tracking systems and their validity in a team sport environment.

A few sport-based vision tracking systems are available on the commercial market including Amisco™ (Sport Universal, Nice, France) (Castellano, Alvarez-Pastor, & Bradley, 2014) and Prozone™ (West Yorkshire, England) (Di Salvo et al., 2006). The validity of Prozone™ for quantifying athlete speed was assessed during running and change of direction movement (Di Salvo et al., 2006). Six recreational athletes performed different running tasks including; 60m straight run, 50m curved run, two sprints (one 15m straight and one 20m with a 90-degree turn) (Di Salvo et al., 2006). Prozone™ was validated against timing gate measurements. Average velocity measured by Prozone™ during the 60m straight and 50m curved run showed near perfect correlation (r = 0.999) with the timing gates. Similarly, sprinting in a straight line and change of direction showed an excellent correlation (r = 0.970). Whilst, it appears Prozone™ is a valid vision-based tracking system, only average velocity was reported in this study. It should be noted, team sport athletes perform multiple changes of velocity during training and matches (Varley, Elias, & Aughey, 2012), therefore, tracking systems should be able to detect continuous changes in velocity.

Vision-based systems have been used as a monitoring tool in a team sport environment. Research has investigated the suitability of vision-based systems for field tests (Rampinini et al., 2007), the activity profile of elite rugby league players (Dave, Craig, Shayne, Ceri, & Kevin, 2009) and the interchangeability to other tracking systems (Buchheit et al., 2014). It is important to note the research in this section has predominately utilised the Prozone™ tracking system.

Eighteen professional soccer players were monitored throughout a competitive season (Rampinini et al., 2007). An incremental running test and a repeated-sprint ability test were performed, and physical performance parameters were total distance, and various velocity intensities (Rampinini et al., 2007). Authors demonstrated a substantial correlation between the incremental running test and total distance (r = 0.58, *large*) and velocities above 14.4 km·h^{-1} (r = 0.65, *large*) and 19.8 km·h^{-1} (r = 0.64, *large*). A *large* correlation was found between the repeated-sprint ability test and distances covered above 19.8 km·h^{-1} (r = -0.60) and 25.2 km·h^{-1} (r = -0.65). It should be noted, the field tests performed in this study should not be used to examine on-field match performance alone, rather the physiological aspects to perform on the field. The physical activity profile of 78 elite rugby league players was assessed during three matches (Dave et al., 2009). The research provides a detailed description of the activity profile of elite rugby league players that can be compared to the data from other team sports utilising different tracking technologies (Table 2.2.2). This study is purely descriptive and has included athletes from two different leagues which complicates the outcomes. To make more accurate inferences from the findings, researchers are advised to use case studies over multiple seasons. Eighty-two highly trained junior soccer players were monitored during training and one match using different tracking technologies (Buchheit et al., 2014). However, in the interest of this section, only the vision-based tracking data will be discussed. When compared to other tracking technologies Prozone™ displayed *moderate* to *large* correlations for total distance and distances covered greater than 14.4 km·h^{-1} (Buchheit et al., 2014). Despite, the promising correlations, data provided by Prozone™ *moderately* overestimated distances across all velocities and peak speed (Buchheit et al., 2014). However, several issues were identified when operating the Prozone™ system that compromised data collection. The following issues were identified; multiple player identification issues, players leaving the designated playing field with no visibility and lack of a separate broadcasting camera feed.

Despite the number of advances in vision-based tracking systems, several limitations make them less attractive for field-based team sports. Vision-based tracking systems are expensive (despite reducing in recent years), still require human intervention after data is captured and may underestimate athlete movement. Furthermore, teams that train and play at various venues are unable to utilise vision-based systems because of the fixed set up. As such, vision-based tracking systems appear to be a limited tool for assessing team sport activity profile.

Wearable devices such as LPS, GPS and accelerometers directly quantify athlete activity as opposed to vision-based systems. These devices are practical, account for many of the limitations and therefore should be used instead of vision-based tracking systems.

2.3.3.4 Local positioning tracking systems

Local positioning systems (LPS) can measure an athlete's position indoors. Radio signalling or ultra-wideband (UWB) is used to connect fixed base stations (i.e. around a playing area) to mobile tags worn by athletes (Hedley et al., 2010; Leser, Baca, & Ogris, 2011). The connection is then used to calculate the distance between a fixed station to a relative position of an athlete, which in turn can quantify real-time or "live" information regarding an athlete's position, displacement, velocity and acceleration. The concurrent validity of a UWB positioning system (Clearsky T6, Catapult Sports) was assessed against a criterion measure (Vicon) (Serpiello et al., 2018). Four activities were performed on an indoor court (walking jogging, maximal acceleration and 45° change of direction). Distance, speed and acceleration in the linear drills substantially differed between 0.2 to 12% (typical error of 1.2 to 9.3%). During a change of direction, *very likely* moderate to large differences was detected. Data filtering was applied to allow comparisons between systems, indicating the UWB system has acceptable validity to assess movement indoors. The accuracy of LPS (Inmotiotec, Austria) in measuring accelerations of soccer-specific movements was compared to Vicon motion-analysis (Stevens et al., 2014). Twelve soccer players performed eight movements involving linear running and running with changes in direction of 90° and 180° at three intensities (jog, submaximal and maximal). The LPS substantially underestimated total distance and average speed by up to 7% for movements involving 180° change of direction. In the same drill with 180° change of direction, accelerations and decelerations were underestimated by up to 9%, whereas 90° changes of direction overestimated these movements by 16%. The largest difference was identified during linear running combined with a 90° turn as peak acceleration was overestimated by 41% (Stevens et al., 2014). The choice of filtering method is an important factor in tracking systems, which explains the large differences, especially for accelerations. In this case, the Kalman filter failed to account for accelerations from a standing position due to a delay of the LPS. The LPS then attempts to 'catch up' by showing a higher acceleration than what took place. It appears LPS is acceptable for average accelerations and decelerations, however, practitioners should approach with caution when quantifying peak acceleration and deceleration.

In a cohort of six trained soccer players, the accuracy of LPS was investigated on three different courses at six different velocities as well as 10 small-sided games (Ogris et al., 2012). The absolute error of all LPS position estimations during all trials, measured against Vicon, was 23.4 ± 20.7 cm. When measuring average velocities, the estimation only varied between 0.1 km h^{-1} and 0.23 km h^{-1}, however, when considering maximal velocities, the estimations differed by up to 2.71 km h^{-1} (Ogris et al., 2012). The LPS provides reliable results for average velocities, however, are less accurate when dealing with more dynamic movements and maximal velocities. The accuracy of soccer specific activity profile was assessed by LPS (Inmotio Object Tracking BV, Amsterdam) (Frencken, Lemmink, & Delleman, 2010). Three males walked and sprinted four soccer-specific courses (straight line running, a 45° turn, 90° turn and all movements combined) each 10 times. Distance and speed recorded by the LPS were recorded and compared to the same variables by measuring tape and timing gates. Distance covered for all courses that included 45° and 90° changes of direction were underestimated by up to 2%. The mean difference between actual distance and distance measured by LPS increased with course length and turning angle (Frencken et al., 2010). With regards to speed, the LPS measured substantially slower compared to actual speed, despite only producing small differences (CV% = 1.3% to 3.9%). It is important to note that whilst sport specific activities were assessed here, the individuals that completed the tasks were not elite athletes. Elite athletes will almost certainly perform these tasks at higher speeds and acceleration. Therefore, if LPS systems are to be utilised to assess elite athletes, validation protocols should be aligned appropriately. Although the error of LPS increases with increasing speeds, the reported differences are small, supporting the accuracy of LPS in measuring team sport movements.

The Wireless ad-hoc System for Positioning (WASP) is an LPS system developed by the Commonwealth Scientific and Industrial Research Organisation. Originally designed to track underground mining vehicles (Hedley et al., 2010), the system was further developed with the Australian Institute of Sport to track athletes during training and matches. Each WASP node, worn by athletes, is measured relative to a position on the field. The displacement and velocity were then able to be calculated both indoors and outdoors (Sathyan, Shuttleworth, Hedley, & Davids, 2012). The validity of the WASP system in an indoor venue was compared to an outdoor venue using static and dynamic movements (Sathyan et al., 2012). An agility test was used often used by professional Australian Football clubs to test an athlete's overall agility and ability to change direction with speed. During a linear and nonlinear course at an outdoor venue, the mean distance error ranged between 1.3% and 3.2% (Sathyan et al., 2012). Results from this study (overestimation) conflict with previous research reporting an underestimation of data (Frencken, Lemmink, & Delleman, 2010). The two main reasons for the observation in data is the type of courses used and the filtering method. Whilst the method used by Sathyan, Shuttleworth, Hedley, and Davids (2012) provided smoother tracking of players, it underestimated the total distance travelled by eliminating sharp turns during the task.

The LPS provides an accurate and reliable method to measure athlete movement profiles. However, there are several factors practitioners should take note when considering field-based team sports such as Australian Football. For example, the size of the playing surface is bigger than most other team sports and the number of athletes training at any given time is more than most other team sports. Outdoor field training with satellite reception makes GPS an attractive option for athlete tracking.

2.3.3.4 Global positioning systems (GPS)

In team sports, parameters derived from GPS technology provides coaching and performance staff a better opportunity to monitor external load during training and competition compared to video-based time-motion analysis (Cummins, Orr, O'Connor, & West, 2013). Given a plethora of research exists, a snapshot describing team sport athlete activity profile in matches is shown in Table 2.2.2. Tracking players using GPS allows for real-time or 'live' monitoring as well as time-efficient reporting to coaches post-training or match (Cummins et al., 2013). In comparison, video-based tracking could take upwards of eight hours to report the same information that can be obtained from GPS in minutes. Several factors exist that contribute to the utility of a GPS device. Many factors include device sampling rate, number of satellites, software/firmware versions and positioning and fitting of devices (Aughey, 2011; Barrett, Midgley, & Lovell, 2014).

Sampling rate is the rate at which a GPS device collects data. Throughout the development of athlete tracking devices, GPS devices have predominantly been utilised with sampling rates of 1 Hz to 15 Hz. In general, measurement precision has improved with increased sampling rate. The sampling rate of GPS devices is a strong focus of reliability and validity studies and this will be discussed below.

Global positioning system satellites orbit the Earth and send information to GPS receivers. The process of the radio signal to reach the GPS devices on earth is the first important step of satellite navigation (Aughey, 2011). The distance from the satellite to the device is derived, and if a minimum of four satellites is connected to the receiver, accurate location can be calculated (Larsson, 2003). Once the location is pinpointed, displacement over a given time can be used to calculate the velocity of athlete movement (Aughey, 2011).

Manufacturer software often includes algorithms to identify poor or missing data. Raw data from commercial software are often filtered by the firmware of the device to reduce the 'noise' or unexplained variability within GPS signal (Malone, Lovell, Varley, & Coutts, 2017). The firmware refers to a written code stored on the device. The type of code and processing is dependent on the individual model and version of firmware; therefore, practitioners must be aware of this influence on their data collection.

It is reported in the literature the contribution of loading from horizontal and vertical planes are likely to be influenced by the anatomical position of the device (Barrett, Midgley, & Lovell, 2014). There is evidence indicating the best anatomical position of an accelerometer is the centre of mass when running (McGregor, Busa, Yaggie, & Bollt, 2009). Further, unit placement was examined during a treadmill protocol (Barrett et al., 2014). Wearing the device between the scapulae did not affect the test re-test reliability and convergent validity of PlayerLoad™ supporting this unit placement during exercise (See Section 2.3.3.5 for more detail). In team sport, the positioning the device at the centre of mass of athletes is impossible due to a few reasons. Most importantly, device placement between the scapulae improves antenna visibility to the sky. Secondly, the centre of mass changes with movement (e.g. running gait) and is an area that athletes generally aim to protect (e.g. contact). Lastly, team sports that include contact such as Australian football and rugby, athletes would be exposed to injury and the devices would be susceptible to damage.

Athlete tracking technology is continually evolving with the factors previously discussed improving. With each advancement, researchers continually set out at determining the validity and reliability of each new device. The following section will review the validity and reliability of GPS devices with different sampling rates. This approach was taken due to the large number of studies investigating each sampling rate thus providing a concise overview of the literature. It should be noted practitioners use different devices for research purposes, but all share the desired outcome of establishing the validity and reliability of athlete tracking technology.

1 Hz GPS devices validity and reliability

One Hz GPS devices displayed *good* concurrent validity when straight-line walking (1.79 $m.s^{-1}$; SEM = 2.7%) and running at low speeds (3.58 $m.s^{-1}$; SEM = 2.6%) compared to measured distance (Portas, Harley, Barnes, & Rush, 2010). With regards to a multi-directional course involving soccer specific movements (designed from video analysis of ten matches), the validity (SEM) ranged from 1.8% to 4.2% when walking and 2.4% to 6.8% when running. However, 1 Hz devices were limited when measuring walking, jogging, striding and sprinting across short distances between 10 and 40 m (Jennings, Cormack, Coutts, Boyd, & Aughey, 2010). Specifically, as the speed of movement increased, the validity decreased. For example, over 10 m, the SEE ranged from 23.8 ± 5.9 (walk) to 32.4 ± 6.9 (sprint). This finding was also consistent for 20 and 40 m distances (Jennings et al., 2010). The findings reported by Jennings et al. (2010) and Portas et al. (2010) identified problems for 1 Hz devices in team sport where high-velocity movements generally occur over short distances.

One Hz devices had *good* to *moderate* (< 8%) intra-unit reliability when measuring linear and non-linear distance over shorter distances (50 to 60 m) during walking and running (Portas et al., 2010) and walking, jogging, running and sprinting over longer distances (> 200 m) (Gray, Jenkins, Andrews, Taaffe, & Glover, 2010). However, the error of 1 Hz devices is *poor* when measuring shorter distances and worsens as speed increases (Jennings et al., 2010). For example, reliability deteriorated when transitioning from walking (CV = 30.8%) to sprinting (CV = 77.2%) over 10 m. In contrast, measuring movements involving a change of direction, the reliability of total distance was promising (CV < 10%) (Jennings et al., 2010). Inter-unit reliability is acceptable for different locomotors speed during linear (CV = 1.5% to 3.4%) and running involving turning and changes of direction (1.6 to 6%) (Gray et al., 2010). However, *poor* inter-unit reliability (CV = 11 to 32%) was reported during high (>14 km·h^{-1}) and very high-intensity running (> 20 km·h^{-1}) (Coutts & Duffield, 2010). Also, evidence indicates the noise of 1 Hz devices (i.e. total error) may exceed the signal (i.e. smallest worthwhile change), indicating these devices may not be able to identify meaningful changes (Jennings et al., 2010) and question 1 Hz devices in their infancy to quantify short, high speed running with changes of direction.

5 Hz GPS devices validity and reliability

Devices that sampled at 1 Hz were largely superseded by 5 Hz. *Good* validity was reported for straight-line distance during walking (SEE = 3.1%) and low speed running (SEE = 2.9%) (Portas et al., 2010) and when measuring varying distances (20 to 8800 m) at different velocities (walking up to 2 m.s^{-1} to sprint > 5.5 m.s^{-1}) (SEE = 0.4 to 3.8%) (Petersen, Pyne, Portus, & Dawson, 2009). Sampling at 5 Hz improved the validity of walking, jogging, striding and sprinting over short distances (Jennings et al., 2010), ranging from 9 to 13% for distances between 20 and 40 m. During a team sport circuit, 5 Hz devices measured total distance with *good* validity (SEE = 3.8 ± 0.6%) (Jennings et al., 2010).

5 Hz devices also had *good* intra-unit reliability (CV < 5%) during straight and non-linear running over distances between ~50 and 200 m (Portas et al., 2010). However, the challenge for 5 Hz GPS device exists for quantifying more complex movements (i.e. repeating 180° turns). The intra-unit reliability of 5 Hz devices was markedly better over 40 m for walking, jogging, striding and sprinting (CV = 6.6 to 9.2%) compared to 10 and 20 m (Jennings et al., 2010). The same authors (Jennings et al., 2010) reported *moderate* intra-unit reliability in two change of direction courses (gradual and tight change of direction) that required athletes to walk, jog, stride

and sprint (CV = 7.9 to 10%). During a simulated running circuit, total distance was measured with *good* reliability (CV = 3.6%). However, the noise (TE = 4.7 m) was greater than the signal (1.1 m) indicating care should be taken when trying to detect small and meaningful changes (Jennings et al., 2010).

Acceleration data from 5 Hz devices displayed acceptable validity for moderate (3 to 5 $m.s^{-1}$; CV = 9.5%) and high (5 to 8 $m.s^{-1}$; CV = 7.1%) starting velocities (Varley, Fairweather, & Aughey, 2012). In contrast to the findings reported by Jennings et al. (2010), the CV was substantially lower than the noise allowing practitioners to confidently detect changes in match running in team sport (Varley, Fairweather, et al., 2012). However, *poor* reliability was reported for low starting velocities (1 to 3 $m.s^{-1}$; CV = 15%) and decelerations (CV = 33%). Varley, Fairweather, et al. (2012) also reported *moderate* intra-unit reliability when starting acceleration velocity was between 3 and 5 $m.s^{-1}$ (CV = 9.5%), however, low and high accelerations, as well as decelerations, displayed *poor* results (CV > 11%). *Moderate* inter-unit reliability was revealed (TEM = 5 to 10%) when measuring for peak speed during a team sport simulated circuit, (Johnston et al., 2012b), but to exercise more caution when assessing speeds over 20 $km{\cdot}h^{-1}$. In summary, the results strongly mandate the validity and reliability between linear and sport-specific circuits are not interchangeable.

10 Hz GPS devices validity and reliability

One study identified that 10 Hz devices are markedly better than 5 Hz devices for quantifying short sprint distance in team sport athletes (Pyne, Petersen, Higham, & Cramer, 2010). The validity of 10 Hz devices (SEE) for short distances was reported as follows: 10 m (13.9%, *poor*), 20m (8.8%, *moderate*), 30 m (6.2%, *moderate*) and 40 m (5%, *good*). The latter findings indicate the accuracy of 10 Hz GPS improved as the distance of short sprints increased. Similar findings were reported when sprints of 30 m compared to 15 m produced smaller error (SEM = 5.1 and 10.9% respectively) (Castellano, Casamichana, Calleja-González, San Román, & Ostojic, 2011). The validity of 10 Hz GPS for total distance during a team sport circuit was assessed against a tape measure (Johnston, Watsford, Kelly, Pine, & Spurrs, 2014). While no substantial difference was reported, the TEM was low (<1%) indicating 10 Hz provides a valid measure of distance.

Intra-unit reliability displayed similar results to validity, improving as short sprint distance increased (TE = 11.7% to 3.8%) (Pyne et al., 2010). In support of these findings, 10 Hz GPS have *good* intra-unit reliability (CV < 5%) for distance during 15 and 30 m sprints (Castellano et al., 2011). Whilst both producing *good* reliability, distances of 30 m had greater stability (CV = 0.7% to 2.8%) compared with 15 m (CV = 1.3% to 3.5%). Inter-unit reliability of team sport athlete movement was *good* for total distance (TEM = 1.3%), peak speed (TEM = 1.6%) and for low- and high speed distance (0 to 19.99 km·h^{-1}; TEM = 1.7 and 4.8% respectively) but not speeds over 20 km·h^{-1} (TEM = 11.5%) (Johnston et al., 2014).

10 Hz have markedly better validity than 5 Hz during different starting acceleration velocities (Varley, Fairweather, et al., 2012). Interestingly, as the starting velocity increased so did the precision (CV = 5.9% to 3.6%). However, consistent with 5 Hz devices, when considering decelerations, the validity is *poor* (CV = 11%). It should be noted that increasing the sampling rate improved the accuracy when decelerations were occurring despite reporting *poor* results. To date, no studies have explored the intra-reliability of velocity data from devices sampling at 10 Hz (Kelly, Scott, & Scott, 2014). The inter-unit reliability of 10 Hz GPS provided promising results for constant velocity (CV = 2 to 5.3%) and acceleration (CV = 1.9 to 4.3%) regardless of starting velocity and when decelerations occurred (CV = 6%) (Varley, Fairweather, et al., 2012). The reliability improved for constant velocity and accelerations as the initial speed of the movement increased from 5 to 8 m.s^{-1}. 10 Hz devices showed *good* inter-unit reliability for measuring instantaneous velocity during acceleration (CV = 0.7% to 9.1%) (Akenhead, French, Thompson, & Hayes, 2014). Results indicated as the speed of acceleration increased the inter-unit reliability worsened, warning practitioners to take caution when measuring accelerations over 4 m.s^{-2}. The error for peak speed over 22 km·h^{-1} during a sport-specific circuit was relatively low (TEM = 1.6%) (Johnston et al., 2014). In contrast to the findings of 1 Hz GPS (Jennings et al., 2010), research involving 10 Hz devices identified the noise was much smaller than the signal (Varley, Fairweather, et al., 2012).

15 Hz GPS devices validity and reliability

A higher sampling rate has provided more valid and reliable data as discussed above. Therefore, practitioners decided to investigate a sampling rate of 15 Hz. However, it is important to note 15 Hz devices sampling rate is calculated by augmenting a 5 Hz or 10 Hz GPS combined with accelerometer data (Aughey, 2011; Johnston et al., 2014). One study reported mixed results when measuring total distance using two 15 Hz GPS devices (Johnston et al., 2014). One device reported a difference whereas the other reported no difference making it difficult to interpret the validity of total distance. In contrast, inter-unit reliability of 15 Hz devices was *good* to *moderate* for total distance, peak speed, low- and high-speed running (TEM = 1.9% to 8.1%) (Johnston et al., 2014). However, when high-speed running distance was considered the reliability was *poor* (TEM = 21%). During a simulated circuit that involved repeated jogging, high-speed running and sprinting, 15 Hz devices displayed *good* to *moderate* inter-unit reliability for the following variables (CV); total distance (3%), distances over 14.4 $km{\cdot}h^{-1}$ and 25.1 $km{\cdot}h^{-1}$ (2 to 6%), peak acceleration (10%) and peak speed (1%) (Buchheit et al., 2014). Acceleration and deceleration (> 3 and 4 $m.s^{-2}$) data were *poor* ranging from 31 to 56%.

Although it has been suggested that a higher sampling rate for GPS devices improve validity and reliability (Jennings et al., 2010; Pyne et al., 2010), there appears to be no additional advantage of sampling at 15 Hz. Practitioners should be aware of the limitations associated with GPS devices sampling at 1 and 5 Hz, especially when measuring high-intensity and short linear running. Therefore, from the available literature, 10 Hz devices are identified as the best tracking device for use in team sport.

2.3.3.5 Accelerometer technology

Tri-axial accelerometers are highly responsive motion sensors that measure the frequency and magnitude of movement in three planes (anterior-posterior, mediolateral and longitudinal) (Boyd, Ball, & Aughey, 2011; Krasnoff et al., 2008). Accelerometers measure kinetic energy (motion) and convert that energy to electrical energy, which is translated to acceleration measurement data. Accelerometer data, when downloaded to operator software, has internal storage and transmission ability so that data can be recorded over long periods, and easily viewed during or after bouts of activity. One of the first studies utilising accelerometers measured the energy expenditure of a single human subject (Wong, Webster, Montoye, & Washburn, 1981). Since then, accelerometers have been used to quantify the physical activity of various populations such as youth (Ott, Pate, Trost, Ward, & Saunders, 2000), sedentary (Tudor-Locke & Myers, 2001), elderly (Gerdhem, Dencker, Ringsberg, & Åkesson, 2008) and diseased (Steele et al., 2000). This research prompted sporting practitioners to investigate the potential application of accelerometers. The following section will provide an overview of accelerometry, including the reliability and validity, followed by a summary of accelerometers used in sports.

The intra- and inter-unit reliability of tri-axial accelerometers is acceptable in both laboratory and field settings (Boyd et al., 2011). First, two protocols were conducted on a hydraulic testing machine. Testing protocols were adjusted from previous research (0.35 to 0.64 g) to account for the higher ranges of acceleration (0.5 to 3.4g) that generally occur during Australian football match-play. This approach provides practitioners with confidence the results produced in a laboratory setting are more representative of the accelerations in an Australian football match. *Good* intra- and inter-unit reliability (CV = ~1 % respectively) was observed for each laboratory protocol (0.5 g and 3.0 g). Whilst it is stated players could wear any device, to improve consistency and within-device reliability of data it is recommended for players to wear the same device during training and matches. Second, ten Australian footballers were fitted with a device during a match and reported similar results (CV = 1.9%). The noise was lower than the signal, suggesting accelerometers can detect small meaningful changes during Australian football matches (Boyd et al., 2011). The test-retest reliability and validity of tri-axial accelerometers were explored during two treadmill running protocols (Barrett et al., 2014).

Team sport athlete's maximal oxygen uptake (VO_2), HR and tri-axial accelerometer data, measured at the scapulae and centre of mass, were recorded during a running test (7 to 16 $km{\cdot}h^{-1}$) (Barrett et al., 2014). PlayerLoad™ is an accelerometer measure that is derived from the instantaneous rate of change in acceleration in three planes (Boyd et al., 2011). *Moderate* to *high* reliability was observed for PlayerLoad™ in both locations (ICC = 0.80 to 0.97; CV = 4.2 to 14%). Between-subject correlations for PlayerLoad™ and physiological measures were trivial to moderate (r = -0.4 to 0.3), whereas within-subject correlations were almost perfect (r = 0.9).

When the device was placed at the scapulae, PlayerLoad™ was underestimated by 15% and increased the contribution of the vertical plane to the overall loading (scapulae = 55% vs centre = 49%). The center of mass is considered the criterion location for measuring accelerometers (Halsey, Shepard, & Wilson, 2011). However, as mentioned above, placing the device at the scapulae is recommended by manufacturers to improve the positional signal triangulating by satellites (Barrett et al., 2014). In contrast to conclusions drawn in a previous study (Boyd, Ball, & Aughey, 2011), when assessing repeated PlayerLoad™ measures, the same unit should be worn to avoid between-unit bias. Strong relationships have also been identified between accelerometers and measures of internal and external load in a team sport setting. *Very large* between-subject correlations were identified between PlayerLoad™, HR and ratings of perceived exertion ($r > 0.7$) (Scott, Black, Quinn, & Coutts, 2013) and between total distance covered ($r = 0.7$) (Casamichana, Castellano, Calleja- Gonzalez, San Román, & Castagna, 2013). Caution must be taken when comparing athletes due to differences in running gait (Barrett et al., 2014). Therefore, individual and longitudinal monitoring is recommended practice.

Team sports practitioners have taken interest in utilising accelerometers to quantify external load. The external load of Australian football matches and training were described (Boyd et al., 2013). Differences of PlayerLoad™ were determined between playing position (midfielders, nomadic, deeps and rucks), level (elite and sub-elite) and matches and training. In matches, the midfield group had the highest PlayerLoad™ per minute (16.03 ± 4.21) and between playing levels, the elite group was higher than sub-elite (15.07 ± 2.02; ES = 0.59 ± 0.29). This finding is supported by work reporting midfielders cover greater distances in matches compared to other positions (Brewer, Dawson, Heasman, Stewart, & Cormack, 2010). Substantial differences were observed between training and matches, but small-sided games produced a similar PlayerLoad™ (15.52 ± 4.95, all positions) compared to matches (Boyd et al., 2013). PlayerLoad™ showed similar trends in GPS derived data, however, it appears PlayerLoad™ may be effective at quantifying low-velocity activity (below 2 $m.s^{-1}$) that is underestimated. Further investigation may provide crucial information for team sports practitioners on the effectiveness of PlayerLoad™ to measure activities such as physical contact. Tri-axial accelerometers were used to differentiate between playing levels and position of netball players (Cormack, Smith, Mooney, Young, & O'Brien, 2014). Professional state level players produced greater load per minute (9.96 ± 2.5) compared to recreational players (6.88 ± 1.88, 100% *likely* lower), and across all positions (mean 97% *likely*). These results support the findings in Australian football (Boyd et al., 2013), indicating accelerometers are successful at differentiating external load between playing levels and position in a team sport. Physical load (calculated the same as PlayerLoad™), was *moderately* greater in matches compared with match practice (85%; ES = 1.17), but not offensive and defensive drills (10%; ES = 0.26) (Montgomery, Pyne, & Minahan, 2010). Match practice was played on only half-court compared to matches being played over the full-court, which can explain the disparity in external load. The total number and severity of impacts from collisions during rugby league matches were recorded (Venter, Opperman, & Opperman, 2011). When considering playing positions, forwards had the highest number of impacts in a game (683 ± 295), whilst backs experienced the highest amount of severe impacts over 10 g of force (12 ± 3.2). The authors failed to test the accelerometer for saturation (when a sensor measures a value larger than a dynamic range) potentially creating a limitation of this study (Dang & Suh, 2014; Venter et al., 2011). This finding is indicative of the role of players within the team and provides a greater understanding of the load imposed by players (including the intensity of collisions).

Coaching and performance staff can utilise accelerometers (specifically PlayerLoad™) to quantify and monitor external load for team sport athletes of different playing levels. However, accelerometers do not provide the position of the athlete, therefore, displacement and velocity cannot be calculated. Measuring athlete displacement allows for the calculation of distance covered at different velocities during training and matches. To account for this limitation, accelerometers have been incorporated into micro-technology devices such as GPS.

Table 2.2.2. Activity profile data from competitive Australian football matches.

Reference	GPS device	Sport	Total distance (m)	HVR distance	HVR threshold	Accelerations	Acceleration and deceleration threshold
(Coutts, Quinn, Hocking, Castagna, & Rampinini)	1-Hz	AFL	12939	3880 m	>14.4 $km \cdot h^{-1}$	N/A	N/A
(Aughey, 2010)	5-Hz	AFL	12734	3334 m	4.17 to 10 $m.s^{-1}$	96 accelerations	2.78 to 10 $m.s^{-2}$
Johnston, Watsford, Austin, Pine, and Spurrs (2015)	10-Hz	AFL	13556 (elite)	28.6 $m.min^{-1}$	14.4 to 20 $km \cdot h^{-1}$	Number of efforts ($n \cdot min^{-2}$) Accel (0.46 ± 0.12) Decel (0.57 ± 0.12)	> 2.78 $m.s^{-2}$ < -2.78 $m.s^{-2}$
(Cunniffe, Proctor, Baker, & Davies, 2009)	1-Hz	Rugby union	7227 (backs) 6680 (forwards)	292 m (back) 342 m (forward)	18 to 20 $km \cdot h^{-1}$	5 (backs) 6 (forwards)	> 2.75 $m.s^{-2}$
(Gabbett et al., 2012)	5-Hz	Rugby league	5590 (avg across four positions)	418 m (avg four positions)	> 5 $m.s^{-1}$	8.7 efforts (avg four positions)	Three or more accelerations >2.78 $m.s^{-2}$
Varley, Gabbett, and Aughey (2014)	5-Hz	Soccer	10274	517 m	≥ 5.5 to 10 $m.s^{-1}$	65 ± 21	(≥ 2.78 $m.s^{-2}$)
		AFL	12620	1322 m		82 ± 26	
		Rugby league	6276	327 m		71 ± 38	
(Gabbett, 2010b)	5-Hz	Field hockey	6576 (avg three positions)	58 m (avg three positions)	> 7 $m.s^{-1}$	39 total (avg three positions)	Acceleration > 0.5 $m.s^{-2}$ (over 2 sec)

Note: HVR = high-velocity running; m = meters; 1 $m.s^{-1}$ = 3.6 $km \cdot h^{-1}$.

2.3.3.6 External load and team sport performance

Global positioning system metrics must be viewed within the sporting code that practitioners are involved with. The total and relative distance during training or match is a common GPS metric used to quantify external load. However, measuring distance may be meaningful only when reporting time of training or match play (relative distance). For example, elite Australian footballers covered a total of 13,556 m in a match in comparison to 10,274 m by soccer players (Table 2.2.2), indicating AFL players covered 28% greater distance. However, with regards to relative distance, AFL players reported 129.6 $m.min^{-1}$ in a match, in fact only covering 21% more than soccer players (104 $m.min^{-1}$). It is important to include both measures of distance to understand not only total movement completed but also the intensity of that movement (concerning time). Running thresholds (i.e. velocity bands) across team sports are different as highlighted by high-velocity running in Table 2.2.2. There are evident differences in speed thresholds across football codes as well as activity descriptors. For example, codes may use numbered classifications such as zones one to six or descriptive categories such as walking, jogging, running and sprinting.

Due to the interaction between physical capacity and external load, physical capacity can be used as a valid measure of team performance (Di Salvo, Gregson, Atkinson, Tordoff, & Drust, 2009; Mohr, Krustrup, & Bangsbo, 2003; Mooney, O'Brien, et al., 2011). In soccer, top-class players performed 28 and 58% more high-intensity running and sprinting during matches respectively than their lower-class counterparts. Top-class players also performed better on the Yo-Yo Intermittent Recovery Test (Yo-Yo IRT) level 1 (11%) (Mohr et al., 2003). This is supported by the finding in Australian football that physical capacity, mediated by high-intensity running, was substantially related to ball disposals (a key performance indicator) (Mooney, O'Brien, et al., 2011). Improvements in high-intensity running and Yo-Yo IRT score may increase a player's ability to improve disposal count (kicking and handballing). In professional English soccer, high-intensity activity performed in matches and team success was evaluated (Di Salvo et al., 2009). Teams in the bottom five (919 ± 128 m) and middle ten (917 ± 143 m) performed substantially more high-intensity running compared to teams in the top five (885 ± 113 m). This finding is similar in Italian soccer, where less successful teams covered 11% more high-intensity running, likely to regain possession of the ball compared to more successful teams (Rampinini, Impellizzeri, Castagna, Coutts, & Wisløff, 2009). The difference in findings can be attributed to the dissimilarities in tactical and technical skill between Australian football and soccer.

In terms of individual performance, a greater percentage of low-speed running and less total distance is associated with better performance (Johnston et al., 2012a; Sullivan et al., 2014). In Australian football, better performing players (≥ 15/20 coaches subjective rating of performance) covered less distance (-14%), spent less percentage of time high-velocity running (-17%) and performed fewer (-9%) efforts per minute compared to players who scored ≤ 9/20 (Johnston et al., 2012a). In another study involving Australian footballers, increasing peak speed and speed ($m.min^{-1}$) throughout a match negatively affected objective performance (Sullivan et al., 2014). These findings in Australian football indicate that a player's ability to gain possession of the ball is more important to performance than high-intensity running. Additionally, better players are more effective in positioning themselves to "read" the play better, which requires less physical effort to have a positive influence on the game (Sullivan et al., 2014). The two best predictors of objective performance for nomadic players were walking ($r = -0.28$) and sprinting greater than 7 $m.s^{-1}$ for fixed position players ($r = 0.36$) (Bauer, Young, Fahrner, & Harvey, 2015). However, the relationships were negative, in other words, as players spent more time walking or completed more sprints, the poorer the performance was rated by the coach. For subjective performance, percentage of time spent running over 5.5 $m.s^{-1}$ was positively related to performance ($r = 0.21$). Further analysis stated for every one percent increase in high speed running, the odds of a higher coaches rating was 1.6 times greater.

In team sports, particularly those that involve contact, care should be taken when quantifying external load. The unpredictable nature of Australian football coupled with changes of pace and collisions all contribute to the overall load of each athlete (Young, Hepner, & Robbins, 2012). Global Positioning Systems and tri-axial accelerometer data provide a valid and reliable measure of external load in team sports. Performance staff would benefit from understanding the best approach to quantify and monitor external load that focuses on the parameters specific to their sporting code and cohort of athletes. It appears that better individual performance and team success is associated with the player's technical and tactical skill, rather than their ability to perform high-intensity exercise. However, these findings should not deter practitioners from monitoring such measures in team sport athletes.

2.3.3.7 Internal load

Internal load refers to the physiological or psychological response of the athlete to a given external load (Impellizzeri, Rampinini, Coutts, Sassi, & Marcora, 2004). The internal load of an athlete is critical in determining the stimulus for training adaptation (Impellizzeri et al., 2004) and includes physiological and perceptual responses (Aughey et al., 2015; Buchheit, Morgan, Wallace, Bode, & Poulos, 2015; Impellizzeri et al., 2004). It is important to understand a prescribed external load may elicit different internal responses from individual athletes based on characteristics such as fitness level, injury, wellness and physiological state (Foster et al., 2001; Impellizzeri et al., 2004).

There are several heart rate (HR) based methods for quantifying objective internal load in response to a training stimulus (training impulse; TRIMP). A TRIMP is a measure derived from training duration and maximal, resting and average HR (Morton, Fitz- Clarke, & Banister, 1990). The TRIMP model developed by Banister takes into consideration exercise intensity as calculated by HR reserve and exercise duration (Banister, 1991). The model has since been modified. Edward's TRIMP proposed a HR-zone based method, using different weighting factors for time spent in five defined arbitrary zones (Edwards, 1994). Further, Lucia's TRIMP based their model around ventilatory thresholds with individual weighting factors in three HR zones (Lucia, Hoyos, Perez, & Chicharro, 2000).

An additional method utilising HR called modified TRIMP has been used to measure internal load in team sport athletes (Akubat et al., 2014; Manzi, Bovenzi, Impellizzeri, Carminati, & Castagna, 2013; Manzi et al., 2010; Stagno, Thatcher, & Van Someren, 2007). Modified TRIMP is calculated by multiplying the weighting factor from the blood lactate response by the time spent in five HR zones (Stagno et al., 2007). In professional male hockey players, mean weekly modified TRIMP showed *very large* correlations with percentage changes in $\dot{V}O_{2max}$ (r = 0.8) and velocity at the onset of blood lactate accumulation (r = 0.71). An individualised approach (iTRIMP) was developed to accurately monitor improvements in fitness in endurance athletes (Manzi et al., 2009). This method was applied to assess the relationship between aerobic fitness and training load in soccer players (Akubat et al., 2014; Manzi et al., 2013). *Large* to *very large* correlations were highlighted between iTRIMP and $\dot{V}O_{2max}$ (r = 0.77), velocity at lactate threshold (r = 0.78), onset of blood lactate accumulation (r = 0.64) and Yo-Yo IRT performance (r = 0.69) (Manzi et al., 2013). In contrast, only *small* to *moderate* correlations were evident between iTRIMP and measures of aerobic fitness (r = 0.14 to 0.39) (Akubat et al., 2014). The relationship between iTRIMP and two GPS metrics (total distance and high-intensity running) was also investigated in this study but will be discussed later in this review (Section 2.3.3.9). It appears there is a dose-response relationship between HR measures and changes in fitness, suggesting it may be a valid measure of internal load for team sport athletes.

It is important to note the limitations associated with HR-based measures of internal load. For example, to collect and analyse HR data; 1) a particular level of expertise is required, 2) collating HR information can be time consuming and 3) there is potential for technical error (Alexiou & Coutts, 2008). Further limitations that can influence HR response during exercise include factors such as hydration status and environmental conditions (i.e. temperature) (González-Alonso, Mora-Rodriguez, Below, & Coyle, 1997; Lambert, Mbambo, & Gibson, 1998; Lambert & Borresen, 2010).

Team sports practitioners adopted quantifying subjective internal load utilising the session RPE method (Foster et al., 2001). Research protocols have suggested players rate their exertion level 30 minutes post activity to ensure the athletes rating reflect the whole session or match instead of the most recent intensity (Foster et al., 2001; Impellizzeri et al., 2004). A rating is provided on a scale numbered 0 to 10 that corresponds to a description of "rest" to "maximal" as shown in Table 2.2.3. This rating is then multiplied by the duration of training (minutes) to determine the session RPE reported in arbitrary units.

The session RPE method has been validated for use in football codes such as Australian football (Scott et al., 2013), soccer (Impellizzeri et al., 2004) and rugby (Bradley et al., 2015). Session RPE was tested for validity against internal (HR) and external load (GPS metrics) in Australian football (Scott et al., 2013). Strong correlations existed between HR and total distance (r = 0.80 to 0.83), high-speed running and PlayerLoad™ (r = 0.71 to 0.83). Despite not being able to detect small changes in intensity during short intermittent running bouts, session RPE was deemed a valid and reliable measure of internal load for Australian football (Scott et al., 2013). The session RPE method was applied to monitor the internal load of soccer players (Impellizzeri et al., 2004). Correlations between session RPE and TRIMP ranged from *large* to *very large* (r = 0.50 to 0.85). Similar results were observed in rugby league where *large* within-individual correlations were reported between session RPE, HR and GPS (total distance, high-speed running and impacts) measures (Bradley et al., 2015).

Table 2.2.3. Borg's CR-10 scale modified by Foster et al. (2001).

Rating	Descriptor
0	Rest
1	Very, very easy
2	Easy
3	Moderate
4	Somewhat hard
5	Hard
6	
7	Very hard
8	
9	
10	Maximal

Internal load and team success were examined across six seasons of elite Australian football (Aughey et al., 2015). Internal load was calculated by session RPE from the players that competed in each match (n = 141). Weekly load was *likely* greater for wins (ES = 0.43) but was only *possibly* higher when adjusting for opponent ladder position (ES = 0.29) (Aughey et al., 2015). Indeed, after adjusting for external load, internal load responses may diverge for athletes with different experience, position and aerobic capacity (Gallo, Cormack, Gabbett, Williams, & Lorenzen, 2015). Specifically, players with four to five years' experience had higher load compared to their younger counterparts (ES = 0.44 to 0.51). Ruckmen had *moderately* higher internal load compared to midfielders (ES = 0.82), but because this position is specialised, further research is warranted to identify differences between perceptual load and training drills with an activity profile more similar to this position (Gallo, Cormack, Gabbett, Williams, et al., 2015). Further, for every one second increase in 2-km time trial time, session RPE also increased by 0.2%, so a larger difference in time trial results would equate to a larger effect of session RPE. Similar findings were reported in elite basketball where players who reported lower session RPE scores performed better on the

Yo-Yo IRT (r = 0.68) (Manzi et al., 2010).

The application of differential RPE is currently emerging (Veugelers, Young, Fahrner, & Harvey, 2016; Weston, Siegler, Bahnert, McBrien, & Lovell, 2015). Ratings of perceived exertion were collected for matches as well as differential ratings for breathlessness, leg exertion and technical demand (Weston et al., 2015). There were *small* differences between leg exertion and technical demand (5.5%) and breathlessness (3.5%). When combined, the three differential measures explained 76% of the variance in match RPE, suggesting an enhanced understanding of match load relative to individual components (Weston et al., 2015). However, a limitation of this study in Australian football is the relatively small sample size per player (n = 5), and only describing team-wide data, where it is likely individual differences were observed but not accounted for. Additionally, it is unclear if differential RPE is successful in identifying whether the perception of effort is a physiological or psychological response (Weston, Siegler, Bahnert, McBrien, & Lovell, 2015). In another Australian football team, two measures of session RPE were applied to all training modalities and two applied to only on-field sessions (Veugelers et al., 2016). The study conducted by Veugelers et al. (2016) investigated the relationship between different methods of session RPE and injury and illness and will be discussed in Section 2.4.3.4.

However, despite its application and popularity in sport, session RPE has limitations. The promising relationship with HR-based measures implies the validity of session RPE with measures displaying positive levels of agreement. However, neither has been established as the ‘gold standard’ measure, limiting the interpretation of such results. It is possible, due to non-perfect correlations, there are unexplained aspects of the relationship between session RPE and other measures of internal load. In a study with runners and cyclists, a poor dose-response relationship was discovered between session RPE and changes in time-trial performance (r = -0.039) (Foster, Daines, Hector, Snyder, & Welsh, 1996). Similarly, session RPE was unable to predict performance in elite youth soccer players (Brink, Nederhof, Visscher, Schmikli, & Lemmink, 2010). Coaches of this team prescribed similar timed training sessions (referred to the external load), which then became the determinant of training load throughout the week and not the internal load (Impellizzeri et al., 2005). As expected, session RPE failed to correlate with changes in skinfolds, speed or maximal aerobic power over two rugby league seasons (Gabbett &

Domrow, 2007). Depending on how accurately session RPE is collected, such as all ratings being collected 30 minutes post-training and athletes providing an honest reflection of training, there are potential issues with conformity and incomplete data. Whilst the simplicity, usability and inexpensive nature of session RPE cannot be denied, these observations question its application to dose-response models. Current psychological state can have a substantial influence on an athletes RPE value and can drive differences in the perception of physiological work. Utilising simple monitoring methodology such as perceptual questionnaires can be an effective tool for assessing athlete wellness (Halson, 2014).

2.3.3.8 Measuring training responses using perceptual wellness

Monitoring training has mainly focused on traditional measures of external and internal load (Halson, 2014; Saw, Main, & Gastin, 2015). However, perceptual measures such as wellness questionnaires and diaries offer an easy and cost-effective method to assist in monitoring athlete training responses (Gallo, Cormack, Gabbett, & Lorenzen, 2015; Gastin, Robinson, & Meyer, 2009; Saw et al., 2015). Perceptual measures can be reported quickly (minutes) and efficiently compared to other physiological measures such as blood markers that can take weeks to assess. In an elite sport environment, due to several reasons, training load measures are not “one size fits all”. Reasons may include financial, staff expertise or suitable fit for a cohort of athletes. Internal load measures such as session RPE or HR responses may work for one club but not another. The following section will discuss perceptual wellness as a measure of internal load used to monitor training responses in team sport athletes.

There are many questionnaires aimed to assess how an athlete is coping with training, such as the Recovery-Stress Questionnaire (Kallus, 1995), Recovery-Cue (Kellmann, 2002), Athlete Burnout Questionnaire (Raedeke & Smith, 2001), Daily Analysis of Life Demands for Athletes (Rushall, 1990) and Athlete Distress Questionnaire (Main & Grove, 2009). The use of questionnaires is beneficial to certain cohorts, however, their length, lack of specificity and impractical nature in a sporting environment (Twist & Highton, 2013) has encouraged sports scientists to design and implement their specific questionnaires (Gastin, Meyer, & Robinson, 2012). In a recent survey, 80% of respondents reported their questionnaires were custom-designed compared to Recovery-Stress Questionnaire for Athletes (13%), Profile of Mood States (2%) and Daily Analysis of Life Demands (2%) (Taylor et al., 2012). Practitioners generally included four to 12 explicitly chosen items measured on a one to five or one to 10 Likert scale. Common items chosen were categories such as muscle soreness, sleep duration and quality, fatigue and general wellness (Taylor et al., 2012). The following scale could be used to provide an example of a wellness question used in a sporting environment: fatigue level rated from 0 (feeling as tired as possible) to 10 (feeling no fatigue).

Team sports practitioners have investigated the use of customised questionnaires. Subjective ratings of wellness were sensitive to weekly training manipulations in Australian football (Gastin et al., 2012). Nine wellness items relating to physical and psychological factors were recorded on a five-point Likert scale. Lower scores, associated with players "feeling as good as possible", were observed throughout the season, indicating athletes responding positively to the training and recovery program (Gastin et al., 2012). Wellness scores improved gradually throughout the week to game day ($p<0.001$), to weeks with no competition ($p<0.05$). In another Australian football team, perceptual ratings of muscle soreness, game and training intensity were recorded on a scale adapted from the Borg CR-10 scale ranging from one (no soreness) to 10 (extremely sore) (Montgomery & Hopkins, 2013). Muscle soreness dropped from 4.6 ± 1.1 AU to 1.9 ± 1.0 within six days post-match. There was a *small* substantial increase in muscle soreness in the three days post-game when comparing higher (0.22 ± 0.07 AU; ES = 0.21) and lower (0.50 ± 0.13 AU, ES = 0.37) game load. Relative to competition, training sessions only made *small* contributions to soreness over three days after each session. Authors identified monitoring muscle soreness as a fundamental component when planning training and recovery programs (Montgomery & Hopkins, 2013). The perceptual response was one measure examined following rugby league matches (McLean, Coutts, Kelly, McGuigan, & Cormack, 2010). Fatigue levels (ES = -1.65), overall well-being (ES = -1.64) and general muscle soreness (ES = -1.40) were substantially worse one day post-match and returned to pre-match levels in approximately four days. In rugby league, self-reported wellness was used to identify the contributing factors to the incidence of illness (Thornton et al., 2016). Athletes completed a wellness questionnaire about illness and perceived wellness and muscle soreness on a 10-point Likert scale (poor to excellent). A reduction in overall wellbeing in conjunction with increased training load was a substantial contributor to the incidence of illness (Thornton et al., 2016). However, in this study athletes only completed the questionnaire at the beginning of the week, albeit every week. Players should be regularly monitored to identify the chance of increased risk of illness, especially if training multiple times during the week. The effect of simulated training (to reflect the activity of Australian football) on perceived soreness was assessed (Singh, Guelfi, Landers, Dawson, & Bishop, 2011). Eleven club level Australian footballers completed contact and non-contact simulated circuit. A 10-point Likert scale was used to examine perceived soreness at baseline, one, 24 and 48 hours post-exercise. Perceived soreness was elevated from baseline to immediately 1h post-exercise (ES = 2 to 3.1). Interestingly, perceived soreness was still elevated 24 and 48h post-exercise (ES = 2.5). In each case the contact circuit elicited greater soreness than the non-contact circuit (ES = 1.26 to 1.8). This finding is consistent with players reporting greater soreness post-match (involving greater contact) as opposed to post-training (Singh et al., 2011). High performance staff tends to rely on their custom-designed questionaries specific to their cohort and sport. Despite a lack of scientific evidence, staff are confident in the information provided their custom questionnaires (Taylor, Chapman, Cronin, Newton, & Gill, 2012).

Perceptual measures provide coaching and performance staff with a valuable tool to monitor individual responses to the training program, competition and life as a professional athlete. Questionnaires are simple for athletes to understand and cost-effective to implement into monitoring systems. Importantly, the conversations that occur between practitioners and players because of completing the self-reported questionnaire provide the most value.

2.3.3.9 Relationship between external and internal load

There is increasing interest directed toward the relationship between external and internal load measures, however, despite the recent interest, there is little evidence investigating this approach (Bourdon et al., 2017). Integrated load measures utilised in team sports include parameters such as HR, session RPE and GPS metrics.

Recent literature has provided promising correlations when investigating the relationship between external and internal load variables. An integrated external:internal load ratio was used to assess aerobic fitness in amateur soccer players (Akubat et al., 2014). External and internal load was measured using total distance (TD) and high-intensity distance (HID) and iTRIMP respectively. Internal load was divided by external load to provide two ratios; TD:iTRIMP and HID:iTRIMP. A *large* correlation between HID:iTRIMP and velocity at the onset of blood lactate (r = 0.65) and TD:iTRIMP and velocity at lactate threshold (r = 0.69) indicated the integration of each type of load may assist in assessing fitness (Akubat et al., 2014). In a semi-professional soccer cohort, *very large* correlations were observed between session RPE and TD (r = 0.74) and PL (r = 0.76) (Casamichana et al., 2013). Further, correlations between sRPE and BodyLoad™ (derived measure including accelerations, decelerations, changes of direction and total impacts) ranged from *small* to *moderate* across different rugby league training modalities (Weaving, Marshall, Earle, Nevill, & Abt, 2014). A *moderate* correlation was found between small-sided games and speed training (r = 0.43 and 0.46 respectively), whereas a *small* relationship existed between conditioning and skills training (r = 0.28 and 0.24 respectively). With regards to high speed distance (> 15 $km \cdot h^{-1}$), correlations ranged from *small* (speed; r = 0.16) to *very large* (small-sided games; r = 0.75) (Weaving et al., 2014). Total distance, tri-axial accelerometers and TRIMP explained 62% of the variance in session RPE (Lovell, Sirotic, Impellizzeri, & Coutts, 2013). Similarly, *moderate* relationships were evident between accelerometers, session RPE (r = 0.49) and TRIMP (r = 0.38) in semi-professional basketball players (Scanlan, Wen, Tucker, & Dalbo, 2014). Overall, these studies provide evidence of *small* to *very large* relationships when examining external and internal load measures. The literature encourages practitioners to use both external and internal load parameters in their monitoring systems instead of one measure in isolation. Also, practitioners are also encouraged to develop novel training load measures that integrate external load, internal load and perceptual wellness in combination that can be applied directly to their cohort of players (Gabbett et al., 2017). It should be noted, that while the results from these studies are promising, research combining external and internal load measures in Australian football is lacking.

2.3.4 Derived training measures

Training load can be used to derive additional measures to assist practitioners in the monitoring process. Additional measures of load are typically calculated using the session RPE method such as those presented in Table 2.2.4. The association between derived measures and injury risk is the last study in this thesis; therefore, this relationship will be discussed later in this review (Section 2.4.5). To date, there is little research describing the relationship between derivative training measures and match performance;

and if such measures can be applied to methods other than session RPE. The following sections will introduce the additional measures of load and if available, discuss their relationship to match performance in team sport.

Table 2.2.4. Summary of derived training load measures in the current literature (Williams, Trewartha, Cross, Kemp, & Stokes, 2016).

Training load measure	Calculation	Reference
Internal load (daily/weekly)	Session RPE x session duration (min)	(Foster, 1998)
Cumulative load	Sum of previous 1,2,3 or 4 weeks (7,14,21,28 days) load values.	(Rogalski et al., 2013)
Week-to-week change	Difference between previous and current weeks/days load.	(Cross, Williams, Trewartha, Kemp, & Stokes, 2016; Rogalski et al., 2013)
Monotony	Mean weekly or daily load/SD.	(Foster, 1998)
Strain	Weekly load x monotony.	(Foster, 1998)
Acute:chronic ratio	Acute load (1 week) divided by chronic load (4-week rolling average).	(Hulin et al., 2013; Hulin, Gabbett, Lawson, Caputi, & Sampson, 2015)
Exponentially weighted moving average (EWMA)	λ × (the previous week's cumulative load) + (1 – λ) × (the smoothed load up to that point). The decay factor λ can represent the time constant in which you are interested in.	(Holt, 2004; Williams, Trewartha, et al., 2016; Williams, West, Cross, & Stokes, 2016)

2.3.4.1 Rolling/moving averages

A rolling or moving average (also referred to as cumulative load) is calculated to assess data by creating a series of averages to a full data set or different subsets of the full data set. For example, in team sports, rolling averages are generally used for periods between three days to six weeks (Akenhead & Nassis, 2016). A rolling average can be applied to a wide range of sport-related data such as HR, GPS metrics and training load.

Rolling averages of HR variability (HRV) is an effective way to monitor training adaptation in sport. Heart rate variability refers to the physiological variation in the time between heartbeats (Malik, 1996). A seven-day rolling average was applied to HRV measures in elite triathletes (Plews, Laursen, Kilding, & Buchheit, 2012). The rolling average difference between R-R intervals (peak of the QRS complex) was practically useful for identifying meaningful changes in fatigue (Plews et al., 2012). Specifically, linear regression revealed a *nearly perfect* negative relationship from day one of training to the athlete suffering non-functional overreaching (r = - 0.88) (Plews et al., 2012). In a group of moderately trained males, a 10-day rolling average was used as a daily reference to monitor HRV during endurance training (Kiviniemi, Hautala, Kinnunen, & Tulppo, 2007). If HRV decreased below the 10-day rolling average a modification to reduce training or rest was prescribed. Collectively, these findings indicate a rolling average of HRV is effective for evaluating training adaptation (i.e. changes in fitness and fatigue) and prescription compared to a single value on a given day.

Research involving team sport athletes has used rolling averages to identify the most intense periods of a match. For instance, experienced and inexperienced Australian footballers covered similar total distance and moderate- and high-speed distance during the three-minute mean period for the first three quarters of a match (Black, Gabbett, Naughton, & McLean, 2016). However, during the most intense three-minute period of a match, experienced players covered greater high-speed distances in the second (ES = 0.42) and third (ES = 0.38) quarters. Similarly, a rolling method (distance covered in five minutes from every time point) was compared with a predefined period (distance covered in five minutes every five minutes) to assess high-intensity running in soccer matches (Varley, Elias, & Aughey, 2012). Predefined periods underestimated peak distance up to 25% and overestimated the subsequent period by 31%. With regards to an intense period of play, there was a 52% reduction in running performance using the rolling method compared to predefined one. Researchers are recommended to use rolling averages to provide a more accurate representation of high-velocity running and not underestimate running performance following an intense period of match play (Varley, Elias, et al., 2012).

Rolling averages can be applied to training load data referred to as chronic load, representing the most recent three to six weeks of training. This method is applied to assess injury risk and to calculate the acute:chronic ratio in team sport athletes which will be discussed in Sections 2.4.5.1 and 2.4.5.5 respectively.

2.3.4.2 Exponentially weighted moving averages

An exponentially weighted moving average (EWMA) applies declining weight to older data and is used to smooth out fluctuations in a dataset (Holt, 2004). The average is characterised by computing a weighted average of two variables: (1) the value of the average from the last period and (2) the current value of the variable. The EWMA originated in economics (Muth, 1960) and weather forecasting (Brown, 1959; Holt, 2004), however, remains largely neglected in the sporting environment (Hunter, 1986). A weighted average is relatively easy to calculate and requires minimal data. Similarly, to a rolling average, research utilising the EWMA in the sporting environment is sparse but has been used to explore injury risk in team sports and will be discussed later in this review.

The EWMA can be derived from training load data, which places declining weight on older values and can be calculated using the following equation proposed by Williams, West, et al. (2016):

$$EWMA_{today} = Load_{today} \times \lambda_a + \left((1-\lambda_a)\right) \times EWMA_{yesterday})$$

Where λ is a value between 0 and 1 that represents the decay factor, with higher values discounting older values at a faster rate (Williams, West, et al., 2016). The λ_a is defined:

$$\lambda_a = 2/(N+1)$$

Where N is the time constant which determines the time frame. For example, a value of 0.1 would equate to a time constant of 10 days.

2.3.4.3 Week to week changes or rate of change in load

The rate of change in load refers to the absolute difference between the current and previous week's training load (Rogalski et al., 2013). Currently, a paucity of research exists investigating this concept in team sport settings. No research is available exploring week to week changes in load and performance; therefore, it is difficult to make inferences. However, it could be hypothesised that large changes in training load from one week to the next could negatively affect performance. This notion is investigated in Chapter 4.

2.3.4.4 Training monotony and strain

Training monotony refers to the amount of training variation in any given week of training (Foster, 1998). Monotony is calculated by dividing the mean weekly load by the SD. The following example can be used to interpret monotony data (Comyns & Flanagan, 2013). A high monotony value suggests there is little variation in training load, which may cause concerns for excess fatigue. A small value would indicate good variations in weekly training, allowing for more recovery. Training strain represents the overall training stress from the week of training. It is derived by multiplying the weekly load by monotony (Foster, 1998). A higher week of load combined with high monotony can produce higher levels of training strain (Comyns & Flanagan, 2013).

Only one study exists assessing the effect of strain on team success. In Australian football, strain was used as a covariate in predicting match outcome (Aughey et al., 2015). An additional measure called training-stress balance, which is calculated by dividing weekly load by four-week load (Hulin et al., 2013), was also used. When training-stress balance was calculated using strain, it was one of the better predictors of match outcome in this football cohort (ES = 0.51). Coaches can manipulate the acute training stress balance to improve the chance of winning matches and coaches should be aware of the recent training strain before prescribing in-season training (Aughey et al., 2015). Training strain and monotony is predominantly used to assess injury risk (Section 2.4.5.4) and calculated using the session RPE method. It is unknown if monotony and strain can be utilised to predict match performance and derived from other measures of training load.

2.3.4.5 Acute:chronic ratio

The acute:chronic ratio represents a load index, which identifies whether an athlete's acute load (one week) is greater or less than what the athlete has been prepared for (chronic load) (Hulin et al., 2015). The ratio is calculated by dividing the acute load by the chronic load as previously described in the literature (Blanch & Gabbett, 2016; Gabbett, 2016; Hulin et al., 2015). The following example indicates how the ratio can be interpreted. An acute:chronic ratio of 0.5 suggests the athlete has only completed half of the training in the current week compared to what was prescribed over the previous four weeks. Whereas, when an athlete has trained twice as much in the current week the athlete would have a ratio of 2.0 (Blanch & Gabbett, 2016).

Comparing acute and chronic load can provide an insight to athlete preparedness (Gabbett, 2016), however, there is no evidence to support the use of the ratio to examine athlete performance.

2.3.5 Quantifying athletic performance

The end goal of a training program in an elite team sport is to improve individual performance and overall team success. Individual match performance, particularly in Australian football, is multifaceted and involves a combination of physical capacity and skill execution (Sullivan et al., 2014). Some research has utilised subjective coaches rating of a player's performance as a valid tool of overall match performance (Johnston et al., 2012a; Mooney, O'Brien, et al., 2011). Most coaches in the AFL are past players with vast experience and have a deep understanding of specific roles within a team, which can reflect a true indicator of match performance. However, higher calibre players can be favoured by coaching staff (Johnston et al., 2012a) and ratings can be dependent on factors such as opposition and tactics.

Objective match-play statistics are commonly used to assess performance in multiple team sports. For example, more shots on goal, better passing and more headers and tackles are associated with more successful soccer teams (Rampinini et al., 2009). In Australian football, there was a general focus on the number of kicks and handballs a player accumulate (disposals). However, a basic number does not truly reflect a player's performance as it depends on how, where and how effective those disposals where (Heasman, Dawson, Berry, & Stewart, 2008). To correct this, a player performance ranking system that considers a player's game time and game situation, was successfully validated (Heasman et al., 2008). A company, Champion Data provides all the statistics for the AFL that claim 99% accuracy (O'Shaughnessy, 2006). Every statistic and position on the field in a match is time-coded within five seconds and within 5 to 10 meters respectively. Champion Data provides a similar ranking system that considers a player's impact upon a match including but not limited to effective and ineffective skill execution.

The Champion Data ranking system has been used as an objective performance measure in the literature. Skill execution is more influential than physical activity profile to player performance as measured by player rank (Sullivan et al., 2014). Specifically, better players may require less physical movement to positively impact a game, highlighting the importance of developing technical and tactical skills; once physical capacity has been established (Sullivan et al., 2014). This finding is consistent with higher calibre players accumulating more disposals per minute (ES = 1.1) and completing less physical activity (ES = 0.7) compared to their teammates (Johnston et al., 2012a). A substantial relationship was observed between the Yo-Yo IRT and the number of disposals through high-intensity running in an Australian football match ($p < 0.1$) (Mooney, O'Brien, et al., 2011). This relationship was moderated by playing position and experience. A similar relationship was investigated involving sub-elite Australian football players (Piggott, McGuigan, & Newton, 2015). Results highlighted a *small* association between physical capacity (3-km time trial) and match performance [direct game involvements (number of kicks, handballs, marks and tackles made) per minute]. An explanation for the small association could be the change in the physical nature of Australian football, rendering the 3-km time trial no longer relevant (Rossignol, Gabbett, Comerford, & Stanton, 2014). In another Australian football team, external load was directly related to match performance measured by an impact ranking system (Gastin et al., 2013). Individual characteristics such as age, experience and pre-season aerobic fitness accounted for almost half of the variation in performance.

The Champion Data Rank score can accurately assess objective performance (O'Shaughnessy, 2006) and has provided associations with physical capacity, match activity profile and player calibre (Johnston et al., 2012a; Mooney, O'Brien, et al., 2011). More importantly, and of relevance in this thesis, research has established a promising relationship between training load and objective performance. However, further investigation is warranted to identify if changes in the weekly training load are beneficial or detrimental to subsequent performance. (Sullivan et al., 2014)

2.4 Monitoring training and team sport injury

Australian football is characterised by repeated physical contact and movements involving endurance, speed and acceleration (Wisbey, Montgomery, Pyne, & Rattray, 2010), which means injuries are inevitable. Most coaching and performance staff agree that injuries are detrimental to individual performance and team success (Hägglund et al., 2013; Raysmith & Drew, 2016). Two main aims of monitoring training in elite sport are to minimise the risk of negative adaptations and ensure athletes are unimpeded by injury and illness. The focus of this section is the association between monitoring training and injury risk in team sport. It is important to note that other complex interactions can also contribute to injury, therefore, the role of these risk factors will also be discussed.

2.4.1 Injury surveillance in football codes

Successful injury management requires injury surveillance (Hoskins & Pollard, 2003). It is difficult to make comparisons between sports due to variations in injury definition, playing levels and seasonal fixtures. However, for football codes such as Australian football, soccer and rugby there are similarities in injury profiles (Orchard & Seward, 2002). The AFL initially defined an injury occurrence as an injury or medical condition which causes a player to miss a match (Orchard & Seward, 2011). This definition is problematic because it only takes into consideration more severe injuries and tends to discount the minor injuries which may cause players to only miss training sessions. Hence a more practical definition has been used in the literature to include missed training sessions (Gabbe, Finch, Wajswelner, & Bennell, 2002; Orchard, Wood, Seward, & Broad, 1998).

Injury rates in elite sport can be measured in a few different ways. In the context of Australian football, injury incidence is measured as "new injuries per club per season" (Orchard, Seward, & Orchard, 2013). In the mid-1990s an individual club was defined as having 40 players and competing in 22 matches. More recently, the average club size has grown to approximately a 47-player squad and 23 rounds. The main measurement utilised by clubs is injury prevalence (the number of missed matches per season) and injury severity, which refers to the number of matches missed per injury (Orchard et al., 2013).

The AFL has conducted an injury surveillance survey at the elite level since 1992. Each year the AFL publishes results in a report examining injuries from each AFL club to identify existing trends. An epidemiological study on injury surveillance in Australian football was conducted over 21 years from 1992 to 2012 (Orchard et al., 2013). Overall, 13,606 players suffered new injuries/illness and 1965 of those injuries reoccurred resulting in a total of 51,919 matches to be missed. Hamstring injuries are the most frequent and common (average of 6 injuries and 20 missed matches per club per season; recurrence rate 26%), despite the rate substantially reducing in 2011 and 2012. In comparison, the most recent data from the 2017 report described slightly lower hamstring injury data (4.9 new injuries and 16.6 games missed; recurrence rate 14%), suggesting improved knowledge and more conservative management of this type of injury. The overall trends in the data indicate injury incidence has stayed fairly constant over time, but players are taking longer to return to play following muscle injuries, with recurrence rates decreasing but severity (number of matches missed) remaining the same (Orchard et al., 2013). Survey information is useful for medical staff to assess their club and the overall injury trends in the AFL compared to other teams. However, this report provides purely raw data and does not examine another other relationship to injury.

2.4.2 Injury risk factors

Injury is a multifactorial process, with several characteristics playing an important role in injury prevention (Drew, Cook, & Finch, 2016). Measurement of a single risk factor provides insufficient information to predict the likelihood of injury (Bennell et al., 1998). Identifying multiple meaningful injury risk factors is the most crucial step in injury prevention (Harvey, 1998). Several contributing risk factors are included in monitoring practices and this information is used by coaches and performance staff for training prescription and management purposes. One major tool used to monitor injury risk includes quantifying training load (both external and internal) and subsequent derivative measures of load (Sections 2.3.4 to 2.4.3). Additional individual characteristics associated with injuries such as age, experience and previous history of injury will also be discussed in this review.

2.4.3 Relationship between training load and injury

Training load can protect from or increase the risk of injury and illness in athletes (Dennis, Farhart, Goumas, & Orchard, 2003; Hulin et al., 2015). According to Cross et al. (2016), there is a ‘U-shaped’ relationship between training load and the risk of injury (Figure 2.8). Low and high training load is associated with an increased risk of injury when compared to moderate training load. The desired area is recognised at the bottom of the ‘U’ which protects the athlete from injury (Cross et al., 2016).

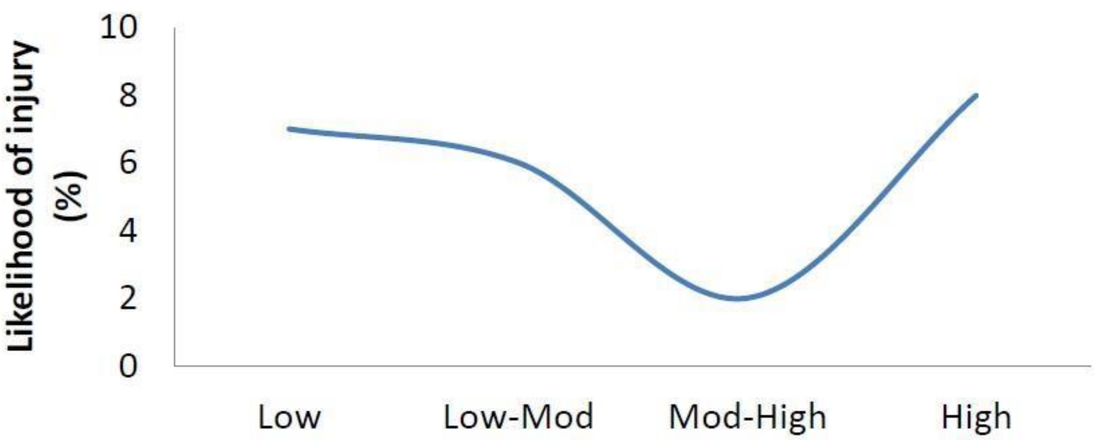

Figure 2.8. The relationship between levels of training load and the likelihood of injury adapted from (Cross et al., 2016).

The relationship between training load and injury in various sports has been evaluated across 33 studies in a systematic review (Drew & Finch, 2016). However, to date, no studies have utilised a combination of external and internal load to assess injury risk in an elite team sport. The following section will discuss training load and associated risk factors, including the notion that training load is the "vehicle" that drives athletes toward or away from injury (Bourdon et al., 2017; Windt, Gabbett, Ferris, & Khan, 2016).

2.4.3.1 External load and injury

In an elite sporting environment, GPS devices are routinely worn during training and matches. Global positioning system data allow the physical activity preceding and following any injury to be examined. For example, professional soccer players performed substantially greater relative distance in the weeks preceding an injury compared to their season average (~7 to 10%; ES = 0.52 to 0.61), indicating an increase in external load leading up to an injury (Ehrmann, Duncan, Sindhusake, Franzsen, & Greene, 2016). Also, weeks preceding an injury showed substantially lower Body Load (accumulation of forces measured by a tri-axial accelerometer) by up to 15%. Periods of un- or over preparedness may lead players to be unable to cope with bouts of high- intensity activity during matches and be more susceptible to injury (Ehrmann et al., 2016). Coaching and performance staff can then aim to expose players to match specific movements to ensure adaptation to match intensity or manage a player's rehabilitation. Additionally, in football codes, where 'live' GPS data is available during training and matches, players can be monitored when unusually high periods of running load is observed. Quantification of movement profiles can assist in external load monitoring and ultimately make informed decisions on individual and team training programs. However, despite its application to an elite team sport, only a relatively small amount of research has explored the relationship between external load (GPS metrics) and injury (Colby, Dawson, Heasman, Rogalski, & Gabbett, 2014; Gabbett, 2010a; Gabbett & Ullah, 2012).

The relationship between external load and injury in team sport athletes is documented in the literature. In elite rugby league, players who performed more than 9 m of high-intensity running (> 7 $m \cdot s^{-1}$) per session were more likely to sustain an injury [Odds ratio (OR) = 2.7] (Gabbett & Ullah, 2012). Authors suggest restricting the amount of sprinting performed in preparation for competition. However, this appears counterintuitive, with reductions in training load can hinder physical preparation and performance. In contrast, when players ran at a moderate intensity (3 to 5 $m \cdot s^{-1}$) the risk was relatively low (OR = 0.4). It should be noted that thresholds in rugby league are generally lower than Australian football due to more bouts of contact and repeated- efforts (Varley et al., 2014). In one elite soccer team, injury and squad management was explored across five seasons (Carling, Le Gall, McCall, Nédélec, & Dupont, 2015). External load measures included total distance and high-speed distance (> 5.3 $m{\cdot}s^{-1}$). Overall, for each season, *very large* to *nearly perfect* correlations existed between average total distance, injury severity (r = 0.9) and missed matches (r = 0.9); and between high-speed distance and muscle strains (r = -0.9), indicating the more you play the more likely you are to get injured. Higher player availability, mediated by functional injury prevention, rehabilitation protocols and recovery strategies, was associated with improved performance (Carling et al., 2015). In Australian football, when velocity load was above 2300 AU in one week during the season, the risk of injury was *small* (OR = 1.9) (Colby et al., 2014). Velocity load is a GPS manufacturer derived measure of running power and momentum (the more continuous and higher the velocity equals a higher-velocity load; GPSports Athletic Data Innovations). Although the risk was only small, practitioners should avoid prescribing large weekly increases in continuous, high-velocity running during the season. In another Australian football cohort, soft-tissue injury risk was examined using external load measures (calculated via GPS) (Esmaeili, Hopkins, et al., 2018). GPS parameters used to derive cumulative measures (i.e. rolling averages) included total distance, PlayerLoad™ and high-intensity running (> 4.17 $m.s^{-1}$). High levels of smoothed PlayerLoad™ over 14 days had the largest effect on injury risk (hazard ratio 3.2; *most likely*). Of the periods investigated, 14 days of was associated with a larger risk of injury for high rolling average and cumulative load measures. Together, these findings challenge performance staff to find the balance between protecting athletes from injury (due to the amount of sprinting or high-velocity running in training) and the consequence of reducing the running load on physical preparation and performance (Gabbett & Ullah, 2012).

External load measured using GPS metrics has potential in injury risk monitoring. The current literature suggests the use of high-speed running variables may be the most important predictors of injury risk in team sport athletes (Colby et al., 2014). Thresholds of high-speed running are different across football codes and individual clubs and therefore, performance staff needs to determine the specific speed bands most practical for their cohort of athletes.

2.4.3.2 Internal load and injury

The findings on external load are consistent with the effect of internal load on injury in team sport athletes. Higher training load is associated with greater risk and injury rates some different team sports including basketball (Anderson, Triplett- McBride, Foster, Doberstein, & Brice, 2003), soccer (Brink, Visscher, et al., 2010), rugby codes (Cross et al., 2016; Gabbett & Jenkins, 2011) and Australian football (Rogalski et al., 2013). To decrease the number and severity of injuries, it is beneficial for coaching and performance staff to understand how athletes respond to the training program.

The most popular measure used to calculate internal load in team sport is the session RPE method, which has been discussed in detail earlier in this review (Section 2.3.3.7). Session RPE allows individuals to estimate the intensity required to perform physical activity (Borg, 1998; Veugelers et al., 2016). In elite women's basketball, a *moderate* correlation was found between weekly training load and injury ($r = 0.6$), suggesting a causal relationship (Anderson et al., 2003). The peak in injuries was related to increased training load, which corresponded to the beginning of competitive matches. The results of this study need to be interpreted with caution due to the relatively low sample size ($n = 12$). In elite rugby union players, a linear relationship was discovered between injury risk and a 2-SD increase (1245 AU) in weekly load (OR = 1.7) (Cross et al., 2016). The results from this study are like those observed in Australian football and professional rugby league players. For example, training load was related to overall injury incidence ($r = 0.8$) including non-contact field ($r = 0.8$) and contact field injuries ($r = 0.8$) in rugby league players (Gabbett & Jenkins, 2011). Another study from Gabbett (2004a) reported more injuries at the start of the season compared to the second half (69% vs. 31%). The incidence of injury was highly correlated to the intensity, duration and load of training, especially in the latter stages of the season when a finals series approach. The research investigating injury risk in Australian football discussed above also examined session RPE (Esmaeili, Hopkins, et al., 2018). It appears the same period (14 days) for rolling average and cumulative load are associated with a larger risk of injury for perceptual responses to training (hazard ratio 2.1 to 2.2). Further, weekly training load between 1750 and < 2250 AU was associated with a risk factor of 2.4 in elite Australian footballers (Rogalski et al., 2013). On the contrary, there was no substantial relationship between internal load and injury in sub-elite Australian footballers (Piggott, 2008). However, the study was limited due to the small sample size (n = 16) and low incidence of injury (n = 5) which influenced the statistical power of this study, therefore, it is difficult to conclude from these results.

Collectively, these results suggest that the harder athletes perceive training, the more likely they are to sustain an injury. Careful load monitoring every week is required to avoid residual fatigue and minimise the effect of training-related injuries in team sport athletes (Gabbett, 2016; Rogalski et al., 2013). It should be noted that a player's perception of effort may be affected by their wellness and how they are feeling at the time of training (Morgan, 1972). This warrants the use of perceptive wellness in monitoring training load.

2.4.3.3 Perceptual wellness and injury risk

Sports injury research is predominantly viewed through physiological and medical factors, but these fail to consider the crucial role of psychological factors (Devantier, 2011). For example, wellness questionnaires exhibit a positive relationship between the dose (wellness questionnaire) and response (training load), making it an attractive monitoring tool for elite athletes with an intense training program (Gastin et al., 2012; Raglin, 2001). Physical and psychological wellness influences the risk of injury in team sport athletes (Ivarsson & Johnson, 2010; Maddison, 2004), however, research investigating the interaction between wellness and the training load-injury risk relationship is scarce. This section will review the available literature utilising wellness to monitor injury risk in a team sport environment.

In elite sport, performance staff generally customise their questionnaires, but evidence to support the use of modified versions is lacking. However, from a practical point of view, staff would be more interested in the validity of the information provided by the customised reports in their cohort of athletes (Taylor et al., 2012). Self-reported questionnaires (84%) were one of the most popular tools utilised by Australian and New Zealand high performance staff (Taylor et al., 2012). Several methods have been identified that prompt changes in the training program (Taylor et al., 2012). One common method is the use of "red flags", often based on arbitrary values determined by performance staff, to identify meaningful changes in the data. Other methods to identify "red flags" include within-player SD and reporting ± 1 SD changes to the mean. Practitioners can use questionnaires to assist in the decision-making process to adapt the training program for individual players (e.g. maintain training, modified sessions or reduced training load) and subsequently load management and injury prevention.

The relationship between wellness and injury has been previously examined. It is important to note that majority of previous research involving wellness measures and injury have used questionnaires that have taken up to four minutes to complete (Drew & Finch, 2016; Ivarsson & Johnson, 2010; King, Clark, & Kellmann, 2010). For example, in a study involving league soccer players, five separate questionnaires had to be completed (Ivarsson & Johnson, 2010). Whilst factors such as “high stress” were associated with greater injury risk, the extensive methodology would be impractical in a busy elite athlete environment.

The Recovery Stress Questionnaire for Athletes was used to monitor changes in stress and recovery of amateur rugby league players (King et al., 2010). The scale consisted of 12 basic scales and 19 sub-scales rated on a six-point Likert scale, which took players between 10 and 12 minutes to complete. Although relevant information about the athlete’s recovery-stress state was provided, the time required to complete the questionnaire may negatively affect players as the season progresses. Wellness scales that take longer to complete could be better suited to being used only a few times during the season. One-minute wellness questionnaires have higher compliance and are easier to implement (Drew & Finch, 2016; Gastin et al., 2012). The relationship between training load, injury incidence and psychological data during pre-season was investigated in rugby league players (Killen, Gabbett, & Jenkins, 2010). Players rated their sleep, food, energy, mood and stress on a 10-point scale (one being poor and 10 being excellent) before two training sessions per week. Whilst there was no substantial relationship, there was an evident linear trend toward higher injury rates with greater psychological scores (rho = 0.5). These findings could be the result of the low incidence of injury (n = 20) or due to the data collection period only being 14 weeks. The authors indicated players were able to train harder when they felt healthier (or psychological scores were higher) which in turn increased the incidence of injury.

The evidence supports the use of perceptive wellness measures in an applied sport setting, particularly to identify athletes at risk of injury. There is a plethora of categories/scales available to monitor athlete wellness on multiple scales. In a recent consensus review, Bourdon et al. (2017) purported the practicality of utilising a brief instrument daily, such as wellness, combined with a detailed measure during training and competition.

2.4.3.4 Can high training load protect athletes from injury?

There is a large body of research that associates high training load with an increased risk of injury. On the contrary, there is also evidence demonstrating that high training load has a protective effect against injury (Gabbett & Domrow, 2005; Hulin et al., 2013; Hulin et al., 2015). The underlying mechanism to help explain this notion is the GAS principle. This section will review the literature highlighting a protective effect of high load followed by a discussion of GAS.

Team sport athletes who completed more than 18 weeks of training before sustaining their first injury were at a reduced risk of a subsequent injury (Gabbett & Domrow, 2005). It should be noted the risk of injury was still *moderate* when players completed less than 18 weeks (OR = 8.7) compared to when athletes completed between 18 to 24 weeks (OR = 4.5). Similar findings have been reported in other team sports (Hulin et al., 2013; Hulin et al., 2015). Elite fast bowlers who delivered a greater number of balls over four weeks reduced the risk of injury from approximately 9% (30 balls bowled) to around 2% (180 balls bowled) in the current and subsequent week (Hulin et al., 2013). In elite rugby league, a high chronic load (> 16,095 m) combined with a moderate two-week acute:chronic ratio (1.02 to 1.18) had the lowest risk of injury (6.2 ± 2.2%) (Hulin et al., 2015). In one Australian football team, four different session RPE measures were calculated to examine injury risk (Veugelers et al., 2016). A substantially meaningful trend was discovered for one-week RPE, one-week session RPE (all sessions) and one-week RPE (field session); the risk of injury was decreased for players who completed higher training load compared to the lower group (OR = ~ 0.08 to 0.2). However, this study was limited due to the number of injuries (n = 13), the inclusion of only non-contact soft tissue injuries and their failure to account for subsequent injuries. Session RPE can be applied to different training modalities, however, preliminary results suggest the exercise intensity of training is more likely to influence the chance of injury rather than overall load (Veugelers et al., 2016).

An introduction about the GAS model can be viewed earlier in this review in Section 2.3.1. When athletes experience high training load the body goes into the “resistance stage” and positive training adaptations occur. However, a continuous high load will lead athletes into the "exhaustion stage". This process can disrupt primary hormone production (i.e. adrenaline, noradrenaline and cortisol), influence behavioural adaptation (neurotransmitter and receptor function) and breakdown on a systematic level (Lachuer, Delton, Buda, & Tappaz, 1994; Meeusen, 1999; Meeusen et al., 2006), and eventually increase the risk of injury. A balance between training stress and adequate recovery is crucial and if successful the effects of training will be positive, reduce injury risk and ultimately improve performance (Bompa & Haff, 1999).

Reducing an athlete's load may not always be the best approach for injury prevention (Gabbett, 2016). However, given that high load can be achieved in different ways through volume, intensity, and frequency of training, high training load should not be viewed with the same injury risk. Overall training load may not be the only contributing factor to injury, rather the modality or type of training prescribed producing the high load.

2.4.4 Periods of intense training load – Pre-season

Periods of training load intensification, such as pre-season, are crucial to developing physical attributes required to compete with the demands of matches (Veugelers et al., 2016). However, periods of intensified training increase the risk of injury (Jones, Griffiths, & Mellalieu, 2017). Athletes returning to complete pre-season after the off-season are also at increased risk of injury due to the detraining effect (Rogalski et al., 2013). Training load is much higher during pre-season than in-season, therefore, it is crucial to accurately control training load to ensure negative training responses, such as injury, are minimised (Borresen & Lambert, 2009; Moreira et al., 2015).

Team sports periodization including different season phases is described in the literature. Training load data was collected across 22 weeks of pre-season and 23 weeks in-season from one Australian football team (Moreira et al., 2015). As expected, a higher training load was completed during pre-season compared to in-season (ES = 0.51 to 1.55; *moderate* to *large*). In another Australian football team, weekly training load was monitored across three pre-season and four in-season blocks (Ritchie, Hopkins, Buchheit, Cordy, & Bartlett, 2016). Similar to the findings of Moreira et al. (2015), total load was *most likely* greater during the pre-season phase, majorly contributed from skill and conditioning sessions. A tapering period was observed in the last pre-season block leading into the competitive season where matches and training made up half of the load experienced by players. Training load was monitored across pre-season and in-season in professional soccer players (Jeong, Reilly, Morton, Bae, & Drust, 2011). Pre-season training load was substantially higher (4343 ± 329 AU) compared to in-season (1703 ± 173 AU). This finding can be explained by the player's completing more frequent and intense training sessions and prescribed fewer rest days in pre-season compared to in-season. The decreased load in-season is a strategy used by coaching and performance staff to account for an increased load of games and reduce the impact fatigue whilst allowing time for recovery (Moreira et al., 2015; Slattery, Wallace, Bentley, & Coutts, 2012).

The effect of training load on injury risk over a pre-season has been investigated in rugby league and Australian football (Gabbett, 2004b; Harrison & Johnston, 2017; Killen et al., 2010; Murray et al., 2016). The literature has utilised both external (GPS metrics) and internal (session RPE) load to investigate this relationship. First, in elite rugby league, Gabbett (2010a) reported a 50 to 80% chance of soft tissue injury when pre-season weekly internal load was between 3000 and 5000 AU. In 62% of cases, a player was considered at risk of injury and no intervention was undertaken, the player sustained an injury (Gabbett, 2010a). The overall incidence of injury was 7 per 1000 hours from 2878 hours of training exposure in another elite rugby league cohort (Killen et al., 2010). Authors reported no substantial relationship between weekly load and injury, however, they identified athletes were at a higher risk of injury during the first half of pre-season when the internal load was higher (8.7 vs 5.3 injury incidence per 1000 training hours). In sub-elite Australian football, when the pre-season internal load was < 1250 AU, athletes were at a higher risk of injury (ES = 0.52 to 0.62) (Harrison & Johnston, 2017). A *small* injury risk (OR = 2.8) was evident in the week following a two-week load period above 4000 AU. In an elite Australian football cohort, the incidence of injury was higher (19 injuries per 1000 training and game hours) than reported in rugby league (Colby, Dawson, Heasman, et al., 2017; Killen et al., 2010). When total distance was very low (< 108 km; OR = 5.6) and low (76 to 88 km; OR = 6.0) during pre-season, players were at a *larger* risk of injury during the in-season phase (OR = 5.6).

The pre-season phase is a high injury risk period for team sport athletes. While higher training load has been linked to improvements in aerobic fitness in this period (Harrison & Johnston, 2017), performance staff must be aware of the risk when prescribing such high load. Monitoring training, particularly during intensified periods, is vital to make sure athletes are provided sufficient recovery. Practitioners must balance training load to maximise improvements in performance without increasing injury incidence.

2.4.5 Derived training load measures to assess injury risk in team sport

The effect of training load on performance can be relatively linked to the effect of load on injury risk (Aughey et al., 2015). An introduction of additional derived measures of load (Table 2.2.4) is briefly described earlier in this review. Such measures have predominantly been used to examine injury risk in team sport athletes; this relationship will be discussed in the following sections.

2.4.5.1 Moving/rolling average

Rolling averages (also referred to as cumulative data) have been applied to training load data to assess injury risk in team sport. A systematic approach was taken to investigate injury prevention in rugby union players (Williams, Trewartha, et al., 2016). Ten derivative measures of load were included in a principal components analysis to identify the most valuable for injury-prevention purposes. Results from one component, which included one to four-week cumulative training load, explained 57% of the variance in injury risk. The four-week cumulative load explained the largest variance in injury risk in the linear model (42%) and deemed an important monitoring tool for injury prevention. Similarly, in Australian football, *larger* one- (>1750 AU, OR = 2.4 to 3.4) and two weeks (>4000 AU, OR = 4.7) cumulative load was associated with greater risk of in-season injury (Rogalski et al., 2013). Results from this study are consistent with findings from Colby et al. (2014). Cumulative GPS load displayed the greatest relationship with injury risk in this Australian football team. During the pre-season phase of the season, three-week total distance (OR = 5.4), sprint distance (distance covered over 75% of maximum speed; OR = 3.7) were associated with the greatest risk. In-season, three-week force load (a measure of running power and momentum; OR = 2.5) and four-week relative velocity change (a function of acceleration, deceleration and change of direction; OR = 2.2) had the highest injury risk (Colby et al., 2014).

In a recent review, Menaspà (2016) expressed concern with the use of rolling averages to assess training load. The following limitations were identified: (1) training adaptations do not fit averages; (2) averages overlook variations within a set period and obscure the overall load patterns; (3) averages do not account for the decline of a training stimulus over time. To illustrate the problem, dummy data was created on three separate graphs for three separate athletes across four weeks of training shown in Figure 2.9 (Menaspà, 2016). It is clear in the figure the three athletes are experiencing very different training load patterns despite having identical injury risk. In response to this review and to address these issues, the use of exponentially weighted rolling averages is proposed (Williams, West, et al., 2016).

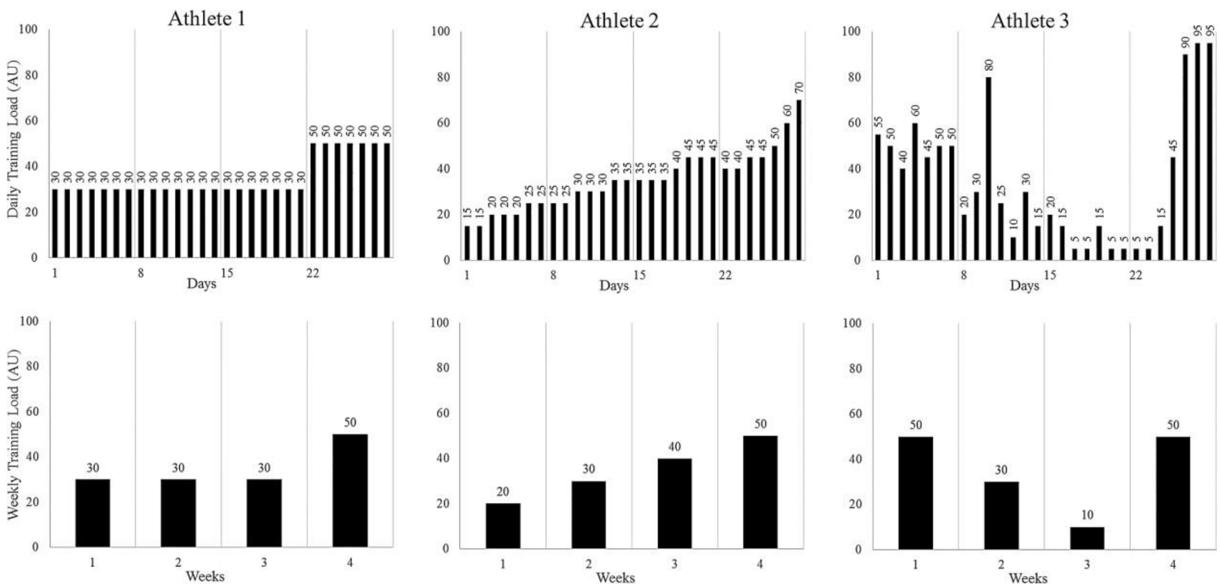

Figure 2.9. Daily training load is shown on the top three graphs, and weekly training load on the bottom. The acute (last week; 50 AU) and chronic (four-week average; 35 AU) training load is the same for each athlete.

2.4.5.2 Exponentially weighted moving average

The EWMA has recently received increasing attention in an applied sports environment. Albeit, only two studies exist that involves EWMA in a team sport. Both studies investigate injury data in rugby league and union players (Kara, 2013; Williams, Trewartha, et al., 2016). As discussed above in section 2.4.5.1, three components were included in the analyses (Williams, Trewartha, et al., 2016). Component one included a 10-day EWMA which accounted for the largest proportion of the variance (57%) in injury risk. Authors concluded that cumulative load is associated with accumulated fatigue leading to an increased likelihood of injury (Williams, Trewartha, et al., 2016). In rugby union, there were clear *harmful* effects of a two-SD EWMA (10-day) on the number of match-related injuries (Kara, 2013). Specifically, all injuries including soft tissue and contact, there was a *likely moderate harmful* effect (ES = 1.32).

This proposed technique appears to provide a novel approach to modelling training data to assess injury risk in elite sport. The formula used to calculate an EWMA is relatively flexible, meaning practitioners can produce different periods as required. For example, researchers have utilised a 10-day average, however, the effectiveness of longer periods (e.g. two to four weeks) is currently unknown. Despite its promise, due to the reasonably small amount of research available, future investigations are warranted.

2.4.5.3 Week to week changes or rate of change in load

The literature available has identified large differences between the current and previous weeks load is associated with increased injury risk in Australian football and rugby union. For example, changes of greater than 1250 AU increased the in-season injury risk in elite Australian footballers by a factor of 2.58 (Rogalski et al., 2013). Similarly, an absolute change in sprint distance (total distance over 75% of individual maximum speed) over 155m increased the injury risk in elite Australian footballers by a factor of 3.2 (Colby et al., 2014). In rugby union, a two-SD increase in the absolute change in load from the previous to the current week (1069 AU; *likely harmful*) resulted in an increased injury risk by a factor of 1.58 (Cross et al., 2016). In another study involving rugby union, week to week changes in load individually accounted for 41% of the variance in injury risk (Williams, Trewartha, et al., 2016).

Findings from the literature regarding week to week changes in training load recommend coaching and performance staff avoid successive heavy and light training weeks. One solution is periodising consistent load throughout the in-season phase to prevent large fluctuations and minimise injury risk. Specific attention should be given to monitoring such measures of individual athletes to assist in load management strategies.

2.4.5.4 Training monotony and strain

Training monotony and strain have predominantly been used to examine injury for athletes. However, research exploring the effect of monotony and strain on injury is conflicting. The impact of training on injury and illness in women's college basketballers was explored (Anderson et al., 2003). A moderately positive correlation was found between weekly injuries, weekly training load ($r = 0.67$) and monotony and strain ($r = 0.67$; $p < 0.01$). An increase in injury was synonymous with an increase in training load, particularly when training started immediately following holidays. Monotony, but not strain, was associated with a *small* risk (OR = 2.6) of traumatic injury in elite youth soccer players (Brink, Visscher, et al., 2010). Additionally, both monotony and strain produced *trivial* results when examining overuse injuries (OR = 0.8 to 1). However, Brink, Visscher, et al. (2010) indicated that the differences in the effect of monotony and strain were dependent on the unit of the variable; monotony and strain had small and large units respectively which in turn dictated the magnitude of the effect. In elite rugby league, there was no substantial relationship between pre-season injury rates and training monotony (r = 0.3) and strain (r = 0.1) (Killen et al., 2010).

Players entering the pre-season phase are required to have a higher base level of fitness allowing them to train at higher intensities and longer periods without increasing injury incidence (Killen et al., 2010). In Australian football, there was no substantial between injury, monotony (r = 0.2) and strain (r = 0.07) across an AFL pre-season (Piggott, 2008). However, as previously discussed, there were very few injuries reported due to performance and medical staff modifying training of players to reduce injury risk and occurrence.

There is potential for the use of monotony and strain to monitor injury risk in athletes because they are easy to calculate and provide information regarding individual responses to the training program. Performance staff are strongly recommended to use monotony and strain in conjunction with weekly load and to implement variations in training stimulus (training type, intensity and duration) to reduce monotony and strain and subsequent injury risk in team sport athletes.

2.4.5.5 Acute:chronic ratio and injury risk

A guide to monitoring injury risk using the acute:chronic ratio in three team sports; cricket, Australian football and rugby league is shown in Figure 2.10 (Blanch & Gabbett, 2016). Practitioners are recommended to aim for an acute:chronic ratio between 0.8 to 1.3, referred to as the ‘sweet spot’ (green shaded area) (Blanch & Gabbett, 2016; Gabbett, 2016). The red shaded area represents the ‘danger zone’ where injury risk is high (ratio over 1.5) (Blanch & Gabbett, 2016; Gabbett, 2016). The use of an acute:chronic ratio provides an insight to athlete preparedness, training patterns, positive and negative training adaptations and crucial information regarding injury risk.

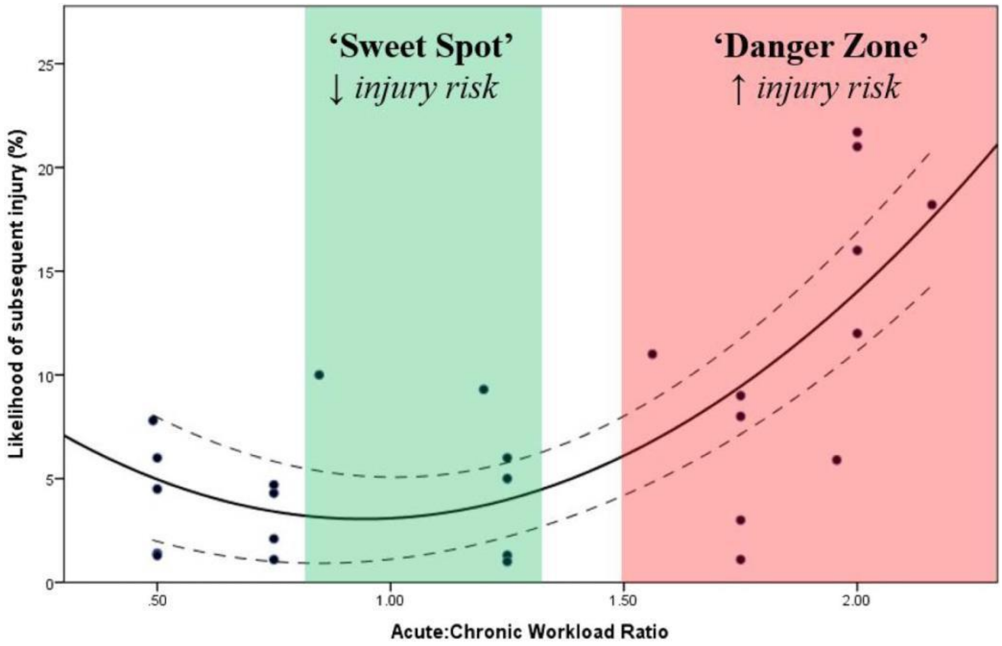

Figure 2.10. A guide to interpreting acute:chronic load data provided by Blanch and Gabbett (2016).

The first study to investigate the acute:chronic ratio and injury risk were conducted with elite cricket fast bowlers (Hulin et al., 2013). Both external (balls bowled) and internal (session RPE) load was monitored in this study. When acute load was similar or less than the chronic load (acute:chronic ratio ≤ 0.99), the likelihood of injury in the next week was only 4%. However, when the ratio was above 1.5, the injury risk was two to four times greater in the subsequent seven days (Hulin et al., 2013). According to Figure 2.10 these results match the 'sweet spot' and 'danger zone' respectively.

The acute:chronic ratio has since been used to assess injury risk and prevention in field-based team sports. In elite rugby league, the association between acute and chronic load and injury risk was investigated (Hulin et al., 2015). The load was calculated using total distance from GPS units sampling at 5-Hz. A very high acute:chronic load ratio (>2.11) substantially increased the injury risk by 16.7% in the current week *(very likely* ≥ 95% risk compared with a low and very low ratio). Additionally, a high chronic load in conjunction with a very high two-week average acute:chronic ratio was associated with the greatest risk of injury (29%) when compared with a moderate ratio (*very likely* ≥ 95% risk). The acute:chronic ratio and injury risk were also examined in a study involving professional soccer players (Malone, Owen, et al., 2017) and elite Gaelic footballers (Malone, Roe, Doran, Gabbett, & Collins, 2016). Soccer players that fit between a ratio of 1 to 1.25 were at substantially lower risk (OR = 0.68), suggesting a protective range for soccer players, which is again consistent with the ‘sweet spot’ range proposed by Blanch and Gabbett (2016). For Gaelic footballers, an acute:chronic ratio of greater than or equal to 2.0 produced the greatest risk of sustaining an injury (Malone et al., 2016). In contrast to soccer players, a range of 1.35 to 1.5 was identified to protect Gaelic footballers from injury during pre-season and early in-season. Aerobic fitness (1km time trial) and experience were included as risk factors in the analysis. When the acute:chronic ratio was greater than 1.5, athletes with only one-year experience (OR = 2.22) and the poor time trial times (OR = 5.10) were at the greatest risk of injury. Authors only included internal load measured by the session RPE method in this study. Research would benefit from including other injury risk factors such as perceived wellness (Halson, 2014), previous injury (Hägglund et al., 2013) and external load. The effect of six different acute:chronic ratios on injury risk and injury likelihood was investigated in elite Australian footballers (Carey et al., 2016). A ratio of 3:21 days best discriminated between high- and low-risk athletes (relative risk = 1.98 to 2.43) in this cohort. However, this finding was evident from one club and one season, therefore other clubs should examine their training load data across multiple seasons to find the ratio best suited for them.

It is important to note some recognised limitations of the acute:chronic ratio. Firstly, risk of injury within the defined arbitrary categories of the acute:chronic ratio, for example as published by Hulin et al. (2015), carry equal risk. Further, the x-axis in Figure 2.10 cannot be treated as a continuous variable and as such the risk of injury is treated as identical despite having different arbitrary categories of load (i.e. high, medium and low groups). Lastly, as discussed above in section 2.4.5.1 there are recognised issues with utilising a rolling average in calculating the acute:chronic ratio. The following limitations will be addressed in Chapter 5.

The acute:chronic ratio provides an important injury risk monitoring tool in team sports. It is important not to generalise or closely compare data between sports due to differences in physical movement profiles. Both external and internal load parameters can be used to derive the ratio, but the size of acute and chronic load windows can strongly influence the ability to inform injury risk (Carey et al., 2016) Acute and chronic load should be monitored by practitioners for injury risk management and training prescription purposes.

2.4.6 Individual characteristics as injury risk factors

2.4.6.1 Age and experience

Age is an important injury risk factor (Gabbe, Bennell, & Finch, 2006) and has implications for training load prescription and management (Gabbett, 2006; Rogalski et al., 2013). However, age cannot be modified to alter an athlete's risk of injury therefore performance staff can control this risk through careful training prescription. The characteristics of junior and senior Australian football players have been described in Section 2.2.4, so the following discussion will describe the relationship between age and injury risk.

Training and injury risk and differences between younger and older team sport athletes are described in the literature. Training load and injury rates were examined across a 14-week pre-season program in junior (~ 17 years) and senior (~25 years) rugby league players (Gabbett, 2006). Overall, senior players had substantially higher weekly internal training load (470 AU) compared to junior players (356 AU). Consequently, injury rates were higher for senior players (121 per 1000 training hours) compared to junior players (56 per 1000 training hours). This may be due to the junior players having greater improvements in physical performance (maximal aerobic and muscular power) as a result of the training program. Gabbe, Bennell, and Finch (2006) also reported older players (> 25 years) who are heavier and have poor hip flexor flexibility are at a higher risk of a hamstring injury. For example, for every kg increase in body weight and 1° in the hip flexor test (decreasing flexibility), the risk of a hamstring injury increased by 7% and 15% respectively. Similarly, at a given training load, older and more experienced. Australian football players were at a greater risk of injury compared to their younger counterparts (Rogalski et al., 2013). Players with two to three (OR = 0.7) and four to six years' experience (OR = 0.7) were at lower risk than players with more than 7 years when training load was above 1650 AU. The same result was evident when an absolute change in the current and previous week was above 1000 AU. Younger Australian footballers who are drafted, usually 17 or 18 years of age, are not as physically developed compared to players who have been exposed to years of higher training load at the elite level (Young et al., 2005). Therefore, the training load of younger players are closely monitored to ensure a smooth transition into an elite training program and to reduce the risk of injury (Rogalski et al., 2013). However, older players are likely to have a history of a previous injury, which is a risk factor in itself (Arnason et al., 2004) and will be discussed in the next section.

Training programs need to be individualised to consider age given training adaptations, exposure to elite level training and injury risk are different. Care should be taken when exposing young players experiencing the training program for the first time and older players who are a greater risk of injury. However, further research should be conducted across multiple seasons to have a greater understanding between the interaction of age and experience as an injury risk predictor in the training load-injury relationship.

2.4.6.2 History of previous injury

The most identifiable injury risk factor is a history of previous injury (Hägglund, Waldén, & Ekstrand, 2006; Hrysomallis, 2013). Players who have been injured are at a higher risk of sustaining the same injury again (Hägglund et al., 2006). Across two seasons of professional soccer, players who were injured in the first season were at a greater risk of sustaining any injury in the following season (hazard ratio = 2.7) (Hägglund et al., 2006). Specifically, players who suffered previous hamstring, groin and knee injuries were two to three times more likely to suffer the same injury in the following season. These findings are consistent with the effects presented by Arnason et al. (2004). *Moderate to large* recurrence rates for hamstring (OR = 11.6), groin (OR = 7.3), knee (OR = 4.6) and ankle (OR = 5.3) injuries were reported from 306 elite male soccer players in Iceland. In an elite Australian football cohort, 34% of players who sustained a hamstring injury had a history of the same injury in the previous 12 months (relative risk = 3.2) (Gabbe, Bennell, Finch, Wajswelner, & Orchard, 2006). Interestingly, players who sustained further injuries were substantially more flexible suggesting an emphasis on mobility work during the rehabilitation phase without reducing injury risk. Different mechanisms exist for different types of injuries, however, the following mechanisms provide likely explanations from sustaining a previous injury; scar tissue as a result of muscle strain, joint instability and altered biomechanics (Orchard, Seward, McGivern, & Hood, 2001; Orchard, 2001; Verrall, Slavotinek, Barnes, Fon, & Spriggins, 2001). The effects of previous history on injury susceptibility need to be considered in conjunction with other risk factors to assist in examining the training load-injury relationship.

2.5 Summary

Most team sports involve regular competition throughout a season. The goal of each team is to win as many games as possible (where success may be defined as winning the league or competition, making the play-offs, avoiding relegation, or finishing with as a high a ranking as possible). There are several factors thought to affect match outcome in such a structured (fixture) competition. These factors include days break between matches, match location, and travel and team characteristics (e.g. age, height and weight). However, there is little scientific evidence substantiating their importance in the modern era. Monitoring training load is crucial to identify an athlete's adaptation to a training program to ultimately aim to improve performance and minimise the risk of fatigue, injury and illness. However, in a team environment, there is even less scientific information available at the individualised level of training prescription and monitoring. Performance staff now has a wealth of external and internal load tools to assist in the monitoring process, each with their contribution to an effective monitoring system. It is important to note that individual teams modify their monitoring systems to suit their training program and cohort of athletes. As such, the relationship between external and internal load has received increasing attention, however, there is no evidence to support the combination of load parameters to examine performance and injury risk in elite team sport athletes. There are also a few derivative measures of load that can be used for monitoring and analysis purposes. Additional measures include rolling average, exponentially weighted moving average, week to week changes, monotony, strain and acute:chronic ratio. Firstly, it is currently unknown if these measures can be applied to measures other than session RPE and if they can be used to assess changes in performance and injury risk. Injury is complex so providing information from a single risk factor is inadequate. An important part of injury risk management is identifying multiple meaningful risk factors such as periods of load intensification (pre-season), playing age/experience and history of a previous injury. Whilst these areas have been investigated to some extent and in isolation to each other in elite Australian football, their collective impact and contribution to the relationship between training, match performance and injury risk remain poorly understood.

AIMS OF THIS THESIS

This thesis aimed to investigate team success and the relationship between a holistic load quantification method, individual match performance and injury risk in an elite team sport.

Specifically:

- Quantify the effect of selected fixture (match location, days break between matches and travel) and team characteristics (player age, height and weight) on match outcome in elite Australian football (Chapter 3).
- Quantify training load using a unique combination of external and internal variables to provide a global training load measure, relative to individual playing position (Chapter 4).
- Validate the global load measure by quantifying the relationship between derived measures of training and match performance in elite Australian footballers (Chapter 4).
- Validate the global load measure by examining the load-injury relationship in Australian football players (Chapter 5).
- Determine the interaction between injury risk factors (pre-season completed, age and previous injury history) and derivative training load measures and injury risk in an elite Australian football cohort (Chapter 5).

CHAPTER 3. FACTORS AFFECTING MATCH OUTCOME IN ELITE AUSTRALIAN FOOTBALL: A 14-YEAR ANALYSIS

3.1 Introduction

The goal of every Australian football team is to win as many matches as possible, which in turn contributes to the team's ranking on the premiership table and ultimately the success of the team. Aspects of the fixture and team characteristics are likely to affect match outcome in team sports, but evidence for some effects in Australian football is limited whereas others remain anecdotal. Aspects include days break between matches (Kelly & Coutts, 2007), match location (Clarke, 2005), travel status (Richmond et al., 2007; Rowbottom & Pickering, 2000), player age (Gastin et al., 2013), and height and body mass of players (Woodman & Pyke, 1991).

A season of elite Australian football consists of 23 competition rounds where each team play 22 matches and has one "bye" round (excluding finals). Each round of matches is generally played over the course of a weekend, with the number of days between matches typically varying from five to eight. The introduction of two new teams in each of 2011 and 2012 created a "bye" round in the seasonal fixture, which increased the break between a match potentially up to ~16 days. A popular notion in the sport is the numbers of days break between matches impacts a player's performance. For example, shorter breaks do not allow sufficient time to recover and prepare for the next match, whereas longer breaks may lead coaches to include additional training to improve on facets of their game such as technical and tactical skill or physical fitness. There is some evidence to support the theory that shorter breaks between matches have a detrimental effect on subsequent performance. For example, it takes up to 72 hours for a countermovement jump to return to the pre-match level after an Australian football match (Cormack, Newton, & McGuigan, 2008). A similar time course was identified when plasma creatine kinase concentration (a marker for muscle damage) took approximately 72 hours post rugby match to return to baseline level (Takarada, 2003). The number of days break plays an important role in training periodization (Kelly & Coutts, 2007), yet the effect of days break on match outcome in elite Australian football is unknown.

Match location in elite Australia football can be considered the most unique of all Australian team sports. From 2012, the Australian Football League has involved 18 teams. Ten of these teams reside in Victoria, and two teams are based in each of Western Australia, Sydney, Queensland and Adelaide. In matches involving teams that have their stadiums, there is a clear "home" and "away" team. However, in matches where the ground is shared, the fixture designates the home and away team. Home advantage was examined from 1980 to 1999 involving 16 teams (Clarke, 2005). From a total of 2299 matches, 1372 matches (approximately 60%) were won by the team with the home advantage (Clarke, 2005). It is possible the perceived home team and designated-fixture home team can be noticeably different (for example the size of the crowd for the away team is substantially greater than the home team). In more recent times, the Australian Football League has introduced playing at additional venues around Australia, which was not included in the previous study. Therefore, the home advantage may have changed over the past ~9 years. Further, home advantage was explored in isolation and did not adjust for factors such as team ability within and across seasons (Clarke, 2005).

Air travel across time zones causes deteriorations in athletic performance (Leatherwood & Dragoo, 2013). This notion is supported by literature in team sports such as Australian netball (Bishop, 2004) and American football (Jehue et al., 1993). Specifically, in Australian football, travelling interstate did not substantially reduce individual player performance, indicating no discrepancy between playing home or away (Richmond et al., 2007). However, this finding may be different at the team level as players were perceived by the coaching staff to perform worse when playing away from home. As the number of teams and venues in the Australian Football League have increased, the number and locations of the travel has increased. The research on travel in the Australian Football League (Richmond et al., 2007) was a single club case study and has not accounted for the recent growth in the number of teams and venues. The influence of interstate travel (which includes crossing up to three time zones) on match outcome in elite Australian Football has yet to be investigated.

Literature considering the relationship between age and performance in Australian football is limited. One study compared starters versus non-starters in one elite Australian Football team (Young et al., 2005).

Starters (mean ± SD: 24.0 ± 3.3 y, 90 matches) were older and had more playing experience compared to non-starters (20.2 ± 2.0 y, 9 matches). Additionally, the older players were physically, technically and tactically superior to their younger counterparts. Age and experience can be considered as confounding variables because playing experience can only ever advance with age (Gastin et al., 2013). While the effect of age on performance has implications for player list management and team selection, the effect of age on match outcome in elite Australian football is unknown.

Research on the effects of anthropometry in Australian football has mainly focused on describing the physical characteristics of players and team selection, but there is none relating to match outcome. In a study of one elite junior Australian Football team, players selected were taller (180.2 ± 7.2 cm) compared with non-selected players (175.3 ± 5.3 cm) (Keogh, 1999). Another study comparing anthropometry between playing levels in Australian football found experienced elite players were heavier (87.55 ± 7.3 kg) compared to inexperienced (86 ± 8.7 kg) and sub-elite players (84.04 ± 9.4 kg) (Bilsborough et al., 2015). Australian Football player characteristic trends have evolved with player height and body mass increasing at a rate of 1.1 $cm.decade^{-1}$ and 1.3 $kg.decade^{-1}$ respectively (Norton, Craig, & Olds, 1999). In one Australian football team, body mass changed by 1.3kg from the start of pre-season to the end of the season (Bilsborough et al., 2016). Anthropometry measures including height and body mass play an important role in team selection (Keogh, 1999; Woodman & Pyke, 1991), but there are no published data on the relationship between anthropometry and match outcome in elite Australian football.

A key role for coaching and conditioning staff in elite Australian football is to plan (periodise) training for the season ahead by taking into account factors, such as the fixture, that may impact the team's chances of winning (Kelly & Coutts, 2007; Robertson & Joyce, 2015). Other key roles for the coaching staff are player recruitment (mainly drafting) and team selection for individual matches. Therefore, this study aimed to quantify the effects of selected fixture and team characteristics on match outcome in elite Australian football.

3.2 Methods

Match statistics of all 5109 Australian Football League matches from seasons 2000 to 2013 inclusive were analysed. All data were retrieved from a freely accessible online source at AFLtables.com where age, body mass and height data were stored from club records in an excel spreadsheet. In the case a player's age, body mass and height changed from season to season, this was reflected in the data set. Data from the online source has been cross-checked before publication against books, newspapers/magazines and online websites. To ensure further accuracy, data from the online source was cross-checked against the official statistics provided by the Australian Football League in 50 randomly chosen matches. All team characteristic data was recorded for each of the 22 players that played in the given match for the entire dataset. Data included all descriptive statistics relating to each match; however, only the fixture and team characteristics are shown in Table 3.1 were included as predictors of winning a match. Therefore, before data analysis, 52 drawn matches were removed from the analysis. This research complies with all relevant codes of experimentation and legislation and has been approved by the Institute human research ethics committee.

Table 3.1. Description of fixture and team characteristics.

Predictor	Description
Match location	Home away vs away match
Travel status	Travelling interstate vs not travelling interstate
Days break	A team experiencing ≥8 d vs ≤7 d break since the last match
Anthropometry	The mean difference age, body mass and height of the team's players in each match classified into quintiles for each season[a].

[a]Quintiles for age, body mass and height were categorised as the following: youngest, younger, similar, older and oldest; lightest, lighter, similar, heavier and heaviest; shortest, shorter, similar, taller and tallest

The logistic-regression version of the generalised mixed linear model (Proc Glimmix) (Schabenberger, 2005) in the Statistical Analysis System (version 9.4, SAS Institute, Cary, NC) was used to estimate the effect of each aspect on match outcome. The fixed effects in the model were match location interacted with travel status, days break, and one of the three anthropometry variables (Table 3.1). Match location and travel status each had only two levels. Days break was a highly skewed variable, with 0.7% of values on 4 and 5 d, 68% on 6 and 7 d, 21% on 8 d, and 11% on ≥9 d. Analyses of this variable grouped into three levels (<7 d, 7-8 d, >8 d) showed little effect, so it was analysed as two levels (≤7 d, ≥8 d) to permit easier analysis of possible individual differences (see below). A separate analysis was performed for each of the three anthropometry variables coded as quintiles of difference between the opposing teams. The effects were evaluated as the fifth and fourth vs the third (middle) quintile. Because of the symmetry in the data arising from equal representation of opposing teams, effects of the first and second quintile were effectively equal and opposite to those of the fifth and fourth quintiles. Quintiles were chosen to allow for the possibility of non-linear effects of the anthropometry variables. A separate analysis was also performed with age and body mass variables both included to adjust the effect of body mass for the potential confounding effect of age, and vice versa. The random effects in the model were the team identity (to account for differences between teams averaged over all years) and team identity interacted with season identity (to account for differences between teams within years). A random effect was included in some analyses to estimate individual differences between teams in the effect of match location, travel status and days break within three groups of seasons (2000 to 2003, 2004 to 2008, 2009 to 2013), but the individual differences are not presented here. Match outcome expressed as win or loss was the dependent variable and was modelled as the log of the odds of a team winning. Least-square means for each level of each fixed effects were expressed as matches won (%); differences between least-squares means were estimated as odds ratios but expressed as differences in percent of matches won or lost against in an otherwise evenly matched opponent (Higham, Hopkins, Pyne, & Anson, 2014); for example, an odds ratio of 1.5 would evaluate as a difference of 10%, with one team on 55% and the other on 45%, while an odds ratio of 1.0 would evaluate as 0%, both teams being on 50%).

Uncertainty in the true effects of the predictors was evaluated using non-clinical magnitude-based inference (Hopkins, Marshall, Batterham, & Hanin, 2009). Effects were deemed clear if the confidence interval for the difference or change in the probability of winning did not include substantial positive and negative values of ±10%, which represent one extra win or loss in every 10 matches (Higham et al., 2014) Magnitudes of clear effects were evaluated as follows: <10%, trivial; 10-30%, small; 30-50%, moderate; >50%, large (Hopkins et al., 2009).

3.3 Results

Fixture and team characteristics are summarised in Table 3.2. Proportions of matches won for each level of the fixture and team characteristic is also shown. Effects derived from the fixture and team characteristics are summarised in Table 3.3. All but one effect was clear at the 99% level. Playing away and travel both resulted in substantial (small) reductions in chances of winning a match. The extreme quintiles of age and body mass difference between opposing teams were also associated with substantial (small) differences in match outcome, with the advantage to the oldest (*most likely)* and heaviest (*likely*) teams. All other effects were trivial. The effects of age and body mass difference were not reduced substantially when adjusted for each other (data not shown).

Table 3.2. Summary of all fixture and team characteristics, with proportions of matches won for each level.

Effect	Home	Interstate travel	Days break	Difference group[a]	No. of matches	Mean ± SD	Matches won (%)[b]
Location*Travel	No	No			983	-	47
	No	Yes			1536	-	35
	Yes	No			2387	-	57
	Yes	Yes			132	-	55
Days break			≤ 7d			6.5 ± 0.5	49
			≥ 8 d			9.2 ± 2.2	50
Age (years)				Oldest		1.8 ± 0.6	67
				Older		0.7 ± 0.2	56
				Similar		0.0 ± 0.2	48
Height (cm)				Tallest		1.8 ± 0.6	44
				Taller		0.7 ± 0.2	51
				Similar		0.0 ± 0.2	48
Body mass (kg)				Heaviest		2.3 ± 0.9	62
				Heavier		0.9 ± 0.4	54
				Similar		0.0 ± 0.2	48

[a]The three groups shown are the fifth, fourth and third quintiles for the difference between the opposing teams for each team characteristic. [b]90% confidence limits all approximately ±5%

Table 3.3. Summary of effects of fixture and team characteristics expressed as extra wins or losses for every 10 matches played.

	Effect; ±90%CL
Location*Travel	
Away vs home (no travel)	-1.0; ±0.4*
Away vs home (travel)	-2.0; ±0.8***
Travel yes vs no (at home)[a]	-0.2; ±0.8^{00}
Travel yes vs no (away)	-1.2; ±0.4**
Away travel vs home (no travel)	-2.2; ±0.3****
Days break	
≤8d vs ≥7d	0.1; ±0.3^{0000}
Age	
Oldest – similar	1.9; ±0.4****
Older – similar	0.7; ±0.4^{00}
Younger – similar	-0.7; ±0.4^{00}
Youngest – similar	-1.7; ±0.4****
Height	
Tallest – similar	-0.4; ±0.4^{000}
Taller – similar	0.3; ±0.4^{0000}
Shorter – similar	-0.3; ±0.4^{0000}
Shortest – similar	0.4; ±0.4^{000}
Body mass	
Heaviest – similar	1.3; ±0.4**
Heavier – similar	0.5; ±0.4^{000}
Lighter – similar	-0.4; ±0.4^{000}
Lightest – similar	-1.1; ±0.4*

[a]Clear at the 90% level; all other effects clear at the 99% level. Substantial effects: *possibly, **likely, ***very likely, ****most likely. Trivial effects: ^{00}likely, ^{000}very likely, ^{0000}most likely (Hopkins et al., 2009).

3.4 Discussion

The main findings of this study were that the effects of playing away, travelling interstate and age difference were detrimental to match outcome, the effect of days break on match outcome was trivial and being heavier was advantageous.

We observed that when playing away (with and without travel) an extra 1 and 2 matches were lost in every 10 games played respectively. This is consistent with the paradigm of home advantage in Australian football with a home team winning percentage of 58% (Josman, Gupta, & Robertson, 2016). The database in this study by including 14 seasons builds on previous research (including only 5 seasons), therefore, increasing the strength of these findings. Fans view crowd effect as a dominant factor in home advantage, however, the effects are difficult to pinpoint (Pollard, 1986). An explanation for the effect of travel is multiple factors interacted such as the influence of territoriality of the home team associated with crowd support and umpire bias to improve home advantage (Pollard, 2006). Eight Victorian teams shared the same two home grounds, which means they generally played at their home ground every second match or sometimes even in consecutive weeks. These matches provide players with greater ground familiarity (such as ground dimensions, climate and tactical positioning), hence lowering the home advantage (Clarke, 2005). However, the latter scenario of two teams both playing at their home ground (with less home advantage) is undermined by the findings in this study (1 extra loss for the away team). In Australian football, two teams can play at the same shared stadium with the fixture designating the home team. In this case, teams with larger crowd support, leading to an imbalance in supporters for their team, may have the home advantage, despite being the designated away team. Umpires are placed under considerable pressure during a match by fans from the home team, which can lead to favourable decisions and enhanced home advantage (Watson, 2013).

The number of venues in the Australian Football League has increased in recent years, which has also increased the amount of travel. One explanation for the travel effect is circadian dysrhythmia, or "jet lag" (Worthen & Wade, 1999). In elite Australian soccer, when several time zones are crossed, travel effects, including presumably jet lag, impair away team performance (Goumas, 2014). Although seven seasons of Australian A-League Soccer were included, only 441 samples involving travel were available for analysis.

In contrast, in this study, a total sample of 1,668 games that involved travel proves strong evidence for the substantial effect found in Australian football. In Australia, the maximum time-zones are crossed is three, the impairments as a result of jet lag may be small, however, when these impairments are added across all players, the effects can be more distinct (Bishop, 2004). The effect of jet-lag in Australian football remains confounded and should be considered for future research. In this study, in support of the literature, the effect is more likely caused by the process of travelling resulting in travel fatigue (Waterhouse et al., 2004). Travellers may suffer from symptoms such as lethargy, confusion and headaches during and immediately after travelling (Waterhouse et al., 2004). Physiological consequences, such as sleep loss as a result of travel, have also been influential in causing poor athletic performance (Youngstedt & O’Connor, 1999). Travelling athletes stay in a different environment compared to home and often must compete at night, which can result in troubled sleep (Halson, 2013; Smith, Ciacciarelli, Serzan, & Lambert, 2000). Further explanations include cramped conditions (including activity restriction) during travel, which increases perceptual fatigue and muscle discomfort (Muhm et al., 2007; Waterhouse et al., 2004). Travel management strategies aimed at mitigating the effects of travel fatigue on players may assist in improving away team performance in Australian football.

The effect of days break on match outcome was trivial. In Super Rugby, a competition formally involving 15 teams from Australia (5), New Zealand (5), South Africa (5), it was suggested that coaches rule out between-match break (days) as a meaningful influence on match outcome (Robertson & Joyce, 2015), supporting the findings from this study. In-season it is likely only one meaningful training session each week can occur to allow adequate recovery before the next match (Aughey et al., 2015; Cormack, Newton, & McGuigan, 2008). It is likely that before the season coaches and performance staff plan and implement strategies to mitigate the effect of days break between matches. Hence, coaching and performance staff may focus on periodising training to allow for recovery and a new training stimulus in-season (Aughey et al., 2015). The inclusion of a bye round (up to 16 days) in the middle of the competitive season, may have a positive effect on players giving them a sufficient balance between recovery, training and rest in-season. An evaluation of the bye round in American football discovered the success of the favourites in the week following the bye (Sung & Tainsky, 2014). This finding supports this study that despite the bye round the stronger teams are generally more successful. Whilst this finding provides an important overview of days break for the entire competition, it is unknown if this effect remains for individual teams.

Our finding that oldest teams experienced a small advantage is consistent with previous research in elite Australian football (Gastin et al., 2013; Young et al., 2005). Greater technical and tactical skill of older players compensated for any decline in physical fitness (Gastin et al., 2013). In another team, starters were older, more experienced and produced better scores representing fitness (ES > 0.8), which can be a result of greater years of exposure to physical conditioning (Young et al., 2005).

Results from this study indicate that the height difference of 1.8 cm in the most extreme quintiles was not enough to make a substantial difference to match outcome. Height might be expected to affect performance via jump height or running speed (i.e. contests and gaining advantages in tactical positioning), and height is a consideration in team selection (Veale et al., 2008). Height is also considered an advantage in certain key positions (e.g., key forwards/defenders and ruckmen) and for defensive skills such as out-marking or spoiling an opponent in a contest (Woodman & Pyke, 1991). These data indicate that the height of players may come into consideration for team selection but does not enhance a team's chances of winning in elite Australian football.

Although the current dogma in Australian football suggests that lighter is better, we found that being heavier is likely to improve team performance. Our analysis accounted for a potential relationship between age and body mass and the findings indicate that the older players were not necessarily the heavier players and vice versa. Therefore, a likely explanation for this effect is players having a higher ratio of lean tissue mass compared to fat mass (relative mass), despite resulting in a heavier body mass overall. This notion, as well as improving strength and power, has been identified in the literature as an important aspect of training for developing professional athletes (Bilsborough et al., 2015). Strong correlations have been identified between anthropometry (fat-free soft tissue mass, fat mass and bone mineral content) and strength characteristics (bench press and jump squat) (Bilsborough et al., 2015). The findings in this study reiterate the importance of strength and conditioning programs in developing relative body mass (increasing lean tissue mass and maintaining low fat mass) as well as preparing player's physically for elite competition.

We acknowledge the limitations of this study; by using data provided by each club to the Australian Football League, the possible effect of other factors on match outcome and potential further changes occurring to the Australian Football League following 2013. Research accessing league-wide and potentially sensitive data (i.e. anthropometry) limits researchers to utilise online sources without having direct access to each club. However, using official statistics provided from each club to the Australian Football League dilutes this limitation. Additionally, data was crosschecked multiple times to ensure an accurate dataset. Any rule changes that have occurred since 2013 in the Australian Football League are directly related to match play and have no bearing on the findings of this study. Despite these limitations, this study provides useful information that relevant practitioners and coaching staff can apply in the field. Unlike any previous research, this study has applied a novel modelling technique involving a large dataset, providing an overview on the effect of specific fixture and team characteristics in elite Australian football across the whole competition.

3.5 Conclusion

Australian football coaching and performance staff can confidently use this information for seasonal training periodization. Specifically, focusing on providing adequate recovery from a match and new training stimuli from week to week may be beneficial. Performance and coaching staff would benefit from implementing strategies to mitigate the negative effects of playing away from home, especially when travelling. Strength and conditioning programs should focus on developing and monitoring a player's relative mass (increasing lean muscle mass and maintaining low fat mass) and strength and power, information that could be used during the player recruitment process.

CHAPTER 4. PROPOSAL OF A GLOBAL TRAINING LOAD MEASURE PREDICTING MATCH PERFORMANCE IN AN ELITE TEAM SPORT

4.1 Introduction

Monitoring training is crucial in identifying an athlete's adaptation to a training program and readiness to train/compete, as well as minimising the risk of non- functional overreaching, injury and illness (Halson, 2014). An athlete response to a training load stimulus can either be positive (improved physical capacity or performance) or negative (increased risk of injury and illness) (Drew & Finch, 2016). High performance staff in an elite environment shares the common goal of keeping athlete's injury-free to prepare players to physically compete and perform. Training load measures have commonly been used to describe injury risk in team sports (Anderson et al., 2003; Rogalski et al., 2013), however, a paucity of research exists examining the training- performance relationship.

Monitoring of training in sport typically involves multiple measures derived from both internal (Banister et al., 1986; Foster et al., 2001) and external load (Boyd et al., 2013; Farrow, Pyne, & Gabbett, 2008), and this can cause a complicated decision-making matrix (See Sections 2.3.3.1 and 2.3.3.7, respectively). The more complicated the matrix, the harder it is for practitioners to make informed decisions. In Australian football, in-season training programs include; "on legs" field, resistance, recovery, and cross-training sessions plus a match every six to eight days (Rogalski et al., 2013). In a team sport environment, individual clubs tailor their monitoring systems to suit the emphasis of their training program. For instance, session rating of perceived exertion (RPE) (Scott et al., 2013) or PlayerLoad™ (Boyd et al., 2013) may work for one club but may not be practical for another. The relationship between match performance and a global training load measure utilising external and internal load in Australian football is currently unknown.

The relationship between external and internal load has received increasing attention in the literature. The total distance (TD) and high-intensity distance (HID) covered in matches by soccer players were divided by individualised training load impulse (iTRIMP; see section 2.3.3.7) to provide two ratios; TD:iTRIMP and HID:iTRIMP (Akubat et al., 2014). A *large* correlation (r = 0.65 to 0.69) between the ratios and aerobic fitness indicated the integration from each type of load is beneficial. Potential future application of external and internal load ratios could be making inferences about fitness levels, fatigue, and readiness to train (Akubat et al., 2014). However, it is important to note these inferences are identified as areas of future research. Furthermore, 62% of the variance in internal load (measured by session RPE) could be explained by external load (measured by distance, impacts and total body stress [accelerations, decelerations and change of direction]) in professional rugby league (Lovell et al., 2013). Research in Australian football examined the relationship between external and internal load (Gallo, Cormack, Gabbett, Williams, & Lorenzen, 2015). Authors indicated several mediators that influence the training load relationship. For example, for a given external load, the perceived load may be different due to the interaction between physical capacity, playing position and experience (Gallo, Cormack, Gabbett, Williams, et al., 2015). Care should be taken when comparing studies that include different training load methodologies, different sports and different sizes of cohorts. These results support the use of both external and internal factors rather than one measure used in isolation; however, there is no evidence to support the combination of load to examine changes in match performance of elite Australian football athletes.

The effect of training load on performance can be partly considered through the prism of the effect of load on injury risk (Aughey et al., 2015). In Australian football, two key injury risk factors include excessive accumulations and large changes in load (Rogalski et al., 2013). The internal load in this study, calculated with session RPE, encapsulated the weekly periodization including the different training modalities (field, weights, cross-training and running conditioning) and the match. An increase of at least 1250 session RPE arbitrary units in the previous week's internal load compared to the current week increased the likelihood of in-season injury (Odds ratio = 2.58) (Rogalski et al., 2013). Training monotony (day to day training variability in each week) and strain (overall stress of the training week) on team sport athletes may also influence match performance (Anderson et al., 2003). In a study involving female collegiate soccer players, 64% of illnesses were associated with monotony and strain, with 53% related to a preceding spike in training load (Putlur et al., 2004). An Australian football team was more successful when training-stress balance calculated using strain was positive (effect size 0.51; ±90% confidence interval 0.41) (Aughey et al., 2015). Training must be carefully managed to avoid residual fatigue and minimise the negative effects of training on injury risk and subsequently match performance. Whilst monotony and strain are valuable monitoring tools, it is not known if they can be applied to measures other than session RPE or weekly rather than daily measures.

The first aim of this study was to quantify load using a unique combination of external (GPS metrics) and internal (wellness responses) variables to provide a global load measure relative to playing position. The second aim was to validate this measure for an elite Australian football team by quantifying the relationship between derived measures of training and match performance.

4.2 Methods

Thirty-six male elite Australian footballers [mean ± standard deviation (SD): age 23.4± 3.2 y; height 188.3 ± 8.0 cm; body mass 88.6 ± 8.5 kg], who all played at least one full senior match during the 2015 season, participated in this study. Players were all registered to one Australian Football League club, which is the highest level of competition for the sport. To obtain a sufficient sample size and to determine whether training measures were affected by position, players were grouped as per their predominant role in the team. If there were instances were a player changed position during a game, their nominated role at the beginning of the game or the role they played the higher game time in was recorded. The total number of players (n), load observations (o), mean ± standard deviation (m) and range of observations (minimum and maximum) for each position were recorded as follows: defenders (n = 13; o = 151, m = 12 ± 8, range = 8 to 22), forwards (n = 13; o = 167, 14 ± 6, range = 4 to 22), midfielders (n = 6; o = 99, m = 18 ± 5, range = 8 to 22) and rucks (n = 3; o = 27, m = 11 ± 8, range = 3 to 19). The study was approved by the Victoria University Human Research Ethics Committee (HRE16-179) and all players provided informed consent in accordance with the Declaration of Helsinki.

All “on-legs” field training sessions and matches were monitored using GPS units sampling at 10-Hz (MinimaxX, Catapult Innovations, Australia). The device was worn in a custom-made playing uniform, fitting the unit in a pouch, between the scapulae. The validity and reliability (coefficient of variation as a percentage) of GPS units have been established in the literature and is acceptable for total distance (1.9

%), high-velocity running (4.7 %), accelerations (4.9 %) and decelerations (11.3 %) (Rampinini et al., 2015; Varley, Fairweather, et al., 2012). Activity profiles were assessed with the following parameters: training and match total distance (m), training and match high-velocity distance (> 5.5 $m.s^{-1}$; m), match average speed ($m.min^{-1}$), match high accelerations (> 3 $m.s^{-2}$) and decelerations (< -3 $m.s^{-2}$). During the competitive season, a typical training week comprised of two main "on-legs" field training sessions, two recovery sessions and one competitive match which were all included for the calculation of load (see Table 4.1). Data were downloaded into proprietary software (Catapult Sprint v5.1.7) and filtered to remove any transition periods (e.g. drinks and quarter breaks), to not underestimate the proportion of high-velocity distance or average speed (White & MacFarlane, 2013).

Table 4.1. Typical training week during a competitive season of Australian football with a seven-day turnaround between matches.

Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Match	Off (recovery)	Recovery	Field training	Off (recovery)	Field training	Match preparation	Match

All players completed a wellness diary in the morning two days post-match to assist in monitoring the recovery process. Categories were chosen based on specific areas of interest to performance staff as previously described (Buchheit et al., 2013). Three main categories titled readiness to train, soft tissue status and overuse/stress risk included 12 items, rated on a 10-point Likert scale ranging from 1 (feeling as bad as possible) to 10 (feeling as good as possible). The individual items were then added together to provide a quantitative score of the overall perceived wellness for each player.

Weekly global load was quantified by combining external load (GPS metrics) variables with internal responses (wellness). Parameters were weighted for two reasons; 1) importance regarding fatigue-inducing load (e.g. high-intensity running) and monitoring susceptibility to injury (see section 2.4.3.1) and 2) to provide an arbitrary unit that could be monitored and interpreted by performance staff with ease (e.g. a number in the hundreds as opposed to the thousands). Performance staff that weighted parameters included the High Performance Manager and Sports Scientist that each has over 20 and 10 year's experience in elite sport respectively. Of these years in elite sport, performance staff was involved with the current Australian football club for approximately five years providing a sound understanding of the playing group to assist in selecting parameters and weighting factors. The following weightings were applied to each variable; total training distance/100, total match distance/100 × 1.5, training high-velocity distance/20, match high-velocity distance/10, match work rate/3, match high accelerations × 10, match high decelerations × 20 and wellness diary score × 3. After the weightings were applied, the resulting measure was expressed in arbitrary units. Two-, three- and four-week rolling means were calculated for load.

Various derivative measures of training load were then calculated. The smoothed load is an exponentially weighted rolling average that accounts for the decaying effects of load using a decay factor λ (lambda) (Hunter, 1986). The smoothed load for each week is calculated as λ × (the previous week's cumulative load) + (1 – λ) × (the smoothed load up to that point). The decay factor λ defines a time constant of 1/λ, which represents the period that contains approximately 2/3 of the total weighting in the calculation of the smoothed load. Smoothed loads were generated with λ values of 0.67, 0.5, 0.33 and 0.25 (time constants of 1.5, 2, 3 and 4 week). The expression for the time constant of 1/λ is different from the value (2 – λ)/λ suggested recently (Williams, West, et al., 2016). This approach was taken to ensure the smoothed load of a given period has the highest correlation with the simple cumulative load of a similar period (Esmaeili, Stewart, et al., 2018).

A formula like smoothed load was used to calculate a predictor variable called differential load, representing the smoothed rate of change in load from one week to the next. In this case, the previous week's load in the above formula was replaced with the change in load between the current and previous week. Differential loads with time constants of 1.5, 2, 3 and 4 weeks were generated.

Training monotony was calculated by dividing the 3-week rolling mean load by the SD of the 3-week of weekly load. Training strain was calculated by multiplying the monotony by the 3-week rolling mean. It should be noted that the method of calculating monotony and strain is slightly different to the traditional approach due to monitoring weekly global load data rather than daily measures (Foster et al., 2001). A ratio of acute:chronic training was calculated by dividing the 1-week load by the 4-week rolling mean (Hulin et al., 2015).

Match performance scores were obtained from Champion Data (Southbank, Australia; http://www.championdata.com.au), the official provider of Australian Football League statistics (Mooney, O'Brien, et al., 2011). The scores are based on effective and ineffective skill execution throughout a match (Sullivan et al., 2014).

The effect of each training measure on match performance was modelled with two separate quadratic mixed models in the Statistical Analysis System (version 9.4, SAS Institute, Cary, NC). First, a simpler model was used to understand the extent to which changes in training alone predicted any changes in subsequent match performance. A within-player SD of the training measure was used to assess the magnitude of the effect of the measure within playing positions; the SD was calculated by taking the square root of the mean of the squares of the players' SD (weighted by the degrees of freedom). Fixed effects in this model were the intercept, the training measure, and the square of the training measure (which together estimate the mean quadratic); the percentage of match-time played was also included as a simple linear effect, because time on field can modify the intensity of activity and potentially performance (Mooney, Cormack, O'Brien, & Coutts, 2013). Random effects in the model were player identity (to estimate different between-player means across the season), the interaction of player identity with the training measure and with the square of the training measure (to estimate individual differences in the players' quadratics), and the residual (within-player match to match variability). A more complex model consisting of additional fixed and random effects was then devised to adjust for potential confounders of the apparent training effects: substitution of players during a match (fixed effects for subbed on or off, each coded as a dummy variable), and match identity (a random effect, to adjust for mean differences in match performance between matches).

Effects of training on match performance were estimated as the change in performance for a typically very low (-2 SD), low (-1 SD), mean, high (+1 SD), and very high (+2 SD) value of the load. Uncertainty in each effect was expressed as 90% confidence limits and as probabilities that the true effect was substantially beyond ± 5 raw units, representing the smallest important change; derived by multiplying 0.2 by the observed-between SD averaged across the position groups. Effects were standardised and interpreted using non-clinical magnitude-based inferences (Hopkins et al., 2009). Thresholds of clear effects were: <0.2, trivial; 0.2 to <0.6, small; 0.6 to <1.2, moderate; 1.2 to <2.0, large.

Reliability analysis of the training measures to determine the magnitude of mean differences between players was performed, since substantial differences would complicate the interpretation of the effects of within-player changes in training on performance. True between-player SD's for each training measure was derived from the reliability analyses. Fixed effects were seasonal trend and problems that caused any adjustments to training (injury or illness, defined as a player not participating in full training, coded as a dummy variable). Random effects accounted for player identity, match identity and match identity interacted with problems.

4.3 Results

Descriptive statistics for all training measures and match performance are summarised in Table 4.2. The true between-player SD's for each training measures were as follows: weekly load, 34; 1.5-week smoothed, 31; 4-week smoothed, 36, 1.5-week differential 3.8; 4-week differential, 3; monotony, 2.1; strain, 1562; and acute:chronic ratio, 0.03. However, the values are relatively small, suggesting no substantial differences between players. Effects of the training measures on match performance derived from the simple model are presented in Table 4.3. Recommendations for training are based on the magnitude of the effect of low or high changes (± 1 SD) in training on match performance (Table 4.3). Predicted match performance scores by a given value of each training measure, two-within player-SD below and above the mean, are displayed in Figure 4.1.

Match performance was generally highest near the mean or ~1 SD below the mean of each training measure. However, *small* decrements in match performance were observed for the following training measures when increased 1 SD above the mean; weekly load for all positions (except rucks), 1.5-week smoothed for all positions (except forwards), 4-week smoothed for rucks, 1.5-week differential for midfielders and forwards, 4-week differential for all positions and acute:chronic ratio for defenders and forwards. Training monotony and strain produced mainly trivial effects; however, *small* reductions in match performance were observed for the following positions when below the mean: rucks (monotony and strain) and midfielders (strain). The effect of two-, three- and four-week rolling averages were mostly trivial or unclear for all positions (data not shown).

Results from the complex model indicated the relationship between integrated load and match performance was not substantially different when adjusted for additional confounding factors. Due to the high volume of data and to avoid duplication, the results from the complex analysis are not shown here. Nevertheless, it is important to note that the effect of training remained causal and was not due to mean changes in training accompanied by mean changes in match performance.

Table 4.2. Descriptive statistics of match performance score and training measures for the playing-position groups.

	Defender	Forward	Midfielder	Ruck
Match performance score[a]	65 ± 27	68 ± 28	101 ± 27	80 ± 21
Weekly load	541 ± 138	576 ± 144	560 ± 135	475 ± 98
1.5-week smoothed load	528 ± 110	557 ± 120	544 ± 112	459 ± 81
4-week smoothed load	482 ± 85	504 ± 98	495 ± 92	406 ± 62
1.5-week differential load	27 ± 108	38 ± 110	33 ± 101	31 ± 86
4-week differential load	20 ± 39	24 ± 38	22 ± 36	23 ± 26
Strain	5334 ± 5917	4676 ± 4665	5649 ± 6782	4070 ± 3130
Monotony[b]	9.3 ± 10.8	7.7 ± 7.1	9.5 ± 10.8	8.5 ± 6.3
Acute:chronic ratio	1.04 ± 0.24	1.07 ± 0.24	1.07 ± 0.23	1.10 ± 0.29

Data presented as mean ± within-player SD. [a]Match performance score, load measures and strain have arbitrary units. [b]Monotony and acute:chronic ratio is dimensionless.

Table 4.3. Effects of the training measures on match performance score derived from the quadratic mixed model.

	Change in match performance score[a] (mean; ±90%CL)		
	-1 SD from the mean load	**+1 SD from the mean load**	**Recommendation for training**
Weekly load			
Defender	**0.9; ±2.9** ^{000}	**-8.3; ±6.2** **	Reduce by 0 to ~1 SD
Forward	**1.7; ±2.9** ^{00}	**-5.8; ±5.7** *	Reduce by 0 to ~1 SD
Midfielder	**5.0; ±4.2** *	**-9.7; ±6.8** **	Reduce by >1 SD
Ruck	-1.0; ±9.3	-0.3; ±10.8	No change
1.5-week smoothed load			
Defender	**-0.5; ±2.9** ^{000}	-4.1; ±5.9 *	No change
Forward	**0.5; ±2.8** ^{000}	-1.1; ±4.9 ^{00}	Reduce by 0 to ~1 SD
Midfielder	**4.4; ±4.1** *	**-5.7; ±5.9** *	Reduce by >1 SD
Ruck	1.2; ±7.8	-8.7; ±13.3 *	Reduce by ~1 SD
4-week smoothed load			
Defender	**-0.9; ±2.9** ^{000}	-2.3; ±5.1 ^{00}	No change
Forward	**-0.8; ±2.8** ^{000}	1.9; ±4.2 ^{00}	Increase by >1 SD
Midfielder	3.5; ±5.3 *	-2.2; ±6.4 ^{00}	Reduce by >1 SD
Ruck	-1.9; ±5.5 ^{000}	-5.3; ±10.8	No change
1.5-week differential load			
Defender	1.3; ±4.0 ^{00}	**-2.9; ±3.8** ^{00}	Reduce by ~1 SD
Forward	1.5; ±4.1 ^{00}	**-4.8; ±3.4** *	Reduce by ~1 SD
Midfielder	3.1; ±6.2 *	**-3.8; ±5.1** *	Reduce by >1 SD
Ruck	8.7; ±10.7 *	0.1; ±5.3	Reduce by >1 SD
4-week differential load			
Defender	**0.5; ±3.1** ^{000}	**-3.6; ±4.4** *	Reduce by 0 to ~1 SD
Forward	**2.1; ±3.0** ^{00}	**-7.6; ±4.1** **	Reduce by ~1 SD
Midfielder	**3.2; ±4.6** ^{00}	**-6.9; ±5.6** *	Reduce by ~1 SD
Ruck	2.8; ±6.4 ^{00}	2.9; ±6.1 *	Reduce by >1 SD
Strain			
Defender	-3.3; ±7.4 *	1.4; ±4.8 ^{00}	Increase by ~1 SD
Forward	0.6; ±6.4	-0.8; ±4.0 ^{00}	Reduce by 0 to ~1 SD
Midfielder	3.3; ±13.0	-3.8; ±8.5 *	Reduce by >1 SD
Ruck	-9.3; ±11.6 *	2.3; ±5.6 ^{00}	Increase by ~1 SD
Monotony			
Defender	-3.1; ±7.6 *	1.4; ±5.0 ^{00}	Increase by ~1 SD
Forward	1.2; ±6.8	-1.0; ±4.0 ^{00}	Reduce by >1 SD
Midfielder	-1.1; ±13.1	-1.9; ±6.9 ^{0}	No change

Ruck	-11.1; ±11.3 **	3.6; ±5.8 *	Increase by ~1 SD
Acute:chronic ratio			
Defender	0.1; ±3.4 ^{000}	**-5.9; ±4.9** *	No change
Forward	**2.6; ±3.9** ^{00}	**-3.4; ±3.7** *	Reduce by ~1 SD
Midfielder	1.0; ±4.9 ^{00}	-1.8; ±5.7 ^{00}	Reduce by 0 to ~1 SD
Ruck	15.1; ±19.5 **	-7.6; ±38.1	Reduce by >1 SD

The effects are the changes in match performance score between the predicted values[b] with confidence limits with probabilistic inferences, and with recommendations for training for playing-position groups. ±90%CL: 90% confidence limits.

Probabilistic inference reflecting a change in the match performance score exceeding the smallest important change (±5 units).

Likelihood for clear substantial effects: *possibly, ** likely, *** very likely, **** most likely.

Likelihood for clear trivial effects: ^{0} possibly, ^{00}likely, ^{000} very likely, ^{0000} most likely.

Results in bold represent effects clear at the 99% level; all others with superscript clear at 90%.

[a] Match performance scores have arbitrary units.

[b] Predicted values refer to Figure 4.1.

1

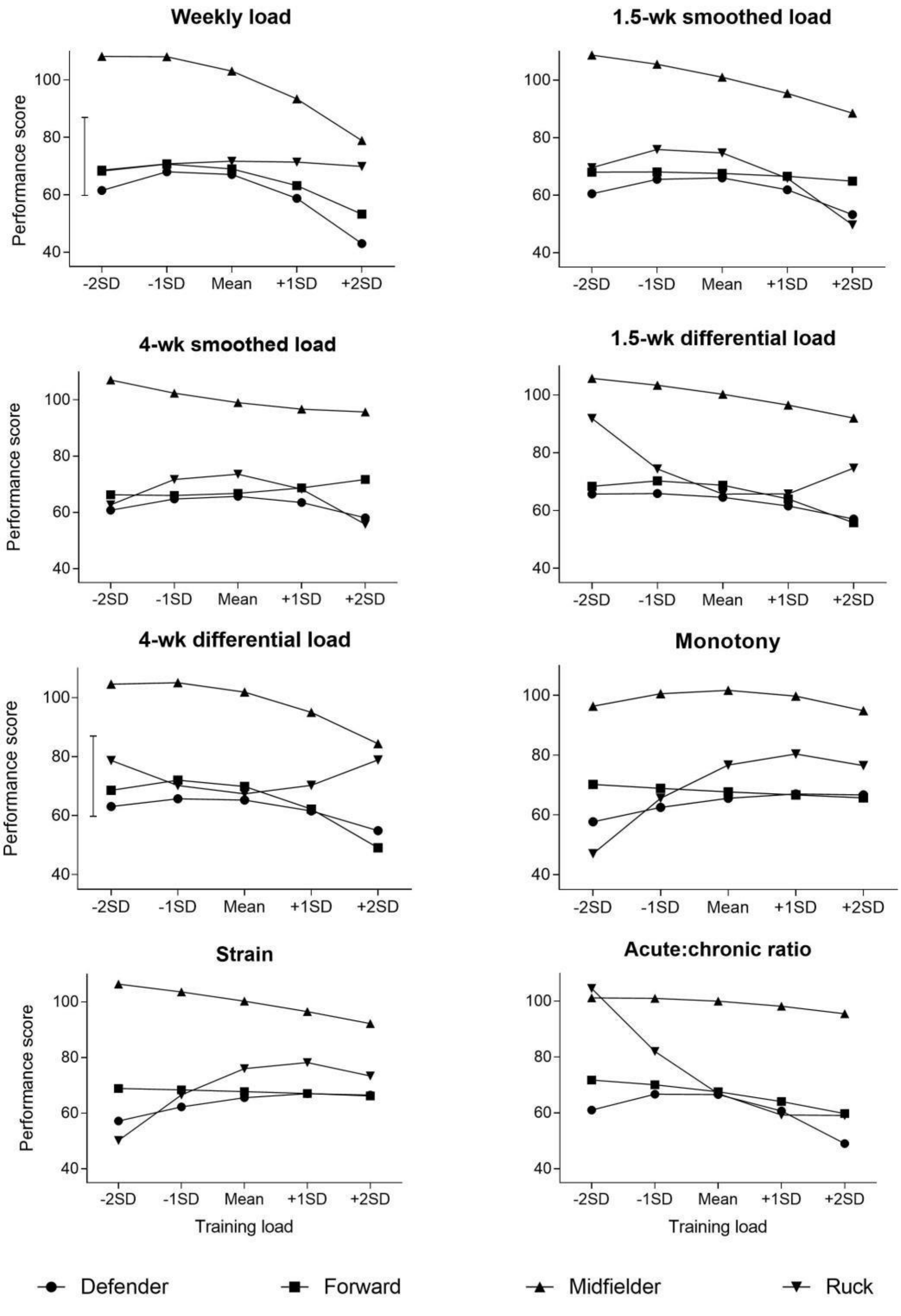

Figure 4.1. The effect of training measures on match performance score. Data are presented as predicted match performance scores for the mean training measure and two within-player SD below and above the mean. The capped line represents the observed between-SD averaged over each position, which is used to derive the smallest important change by multiplying by 0.2. The observed between-SD for all training measures and position groups is approximately 25.

4.4 Discussion

The main findings of this study are: (1) a combination of external and internal load was sensitive to changes in match performance in this Australian football cohort; (2) match performance was typically highest when training measures were at the mean or 1 SD below; (3) match performance was substantially reduced when weekly load (all positions except rucks), 1.5-week smoothed (all positions except forwards) and 4-week differential (all positions) were above the mean; (4) the effects of monotony and strain were mainly trivial; and (5) acute:chronic ratio can also be used as a performance monitoring tool for team sport athletes.

This is the first study to utilize a global training load measure to assess changes in match performance in team sports. We conclude that unique monitoring systems that are specifically designed by performance staff have practical applications in elite Australian football. A system that provides a singular and effective measure of global load can be advantageous to make practical decisions every week for individual players. However, care must be taken when comparing training load between studies or an individual team setting and interpreting results, as the effects of load could be contributed by GPS metrics or wellness measures. Despite being a case study, innovative use of quantifying load and quadratic modelling has been presented here. The results of this study should therefore be treated as promising but preliminary.

When global weekly load was increased above the mean, there were decrements in match performance. Australian football is characterised by repeated high-intensity running interspersed with periods of low-intensity activity (Mooney, Cormack, O'Brien, et al., 2013). Players compete in physically demanding matches every week, which can result in increased muscle damage and fatigue (Mooney, Cormack, O'Brien, et al., 2013). Weekly in-season training periodization typically comprises of six to eight days break between matches, which includes post-match recovery, strength and skill sessions. As it takes up to 72 hours to recover from an Australian football match (Cormack, Newton, & McGuigan, 2008), players may have residual fatigue throughout the remainder of the week, influencing subsequent match performance. Practitioners may benefit from implementing a practical test to monitor neuromuscular function, indicative of fatigue, to adjust training loads as required and improve performance in subsequent matches. Monitoring flight:contraction time of a countermovement jump and comparing pre- to post-match values appears to be the most useful (Cormack, Newton, & McGuigan, 2008). The findings in the current study are in line with a reported decline in match performance in elite Australian footballers who were not sufficiently recovered from the previous match (Hunkin, Fahrner, & Gastin, 2014). The performance decrements were explained by increased pre-match creatine kinase concentration 485% greater than baseline (players in a rested state) (Hunkin et al., 2014). Elevated pre-match creatine kinase may represent incomplete or insufficient recovery from the preceding weeks, indicating the presence of chronic muscle damage. Appropriate recovery is crucial to ensure players are ready to physically compete in matches and avoid compromising their performance.

Increased load over shorter periods of smoothed load (1.5-week) substantially decreased match performance of the midfield group. A key role of the midfielders is to be involved with both attack and defence (McLeod & Jaques, 2006). Midfield players have greater physical requirements as they complete a higher volume of running during matches and training (Wisbey et al., 2010). The latter is supported by one week of increased training load that resulted in greater muscle damage and reduced running performance (decreased peak sprint velocity and total distance covered) during Australian football match simulation (Slattery et al., 2012). A non-motorised treadmill protocol was used to replicate the sport-specific activity profile of Australian football match-play (Sirotic & Coutts, 2007). The period of heavier internal load was sufficient to increase markers of muscle damage, reduce energy production via glycolytic pathways and impair performance (Slattery et al., 2012). It is important to note that the effect of an increase in 4-week smoothed load above the mean was trivial. It appears the fitness acquired from higher loads exceeds the fatigue that induces it (Bingham, 2015). Therefore, it is likely the midfield group improved their stress tolerance to extended bouts of accumulated load which minimised the effect on match performance.

This is the first study to analyse the rate of change in load and match performance in a team sport. Match performance was reduced in all positions after an increase in 4-week differential load. In a study involving tennis players, a 4-week overloading training period evoked higher symptoms of perceptual stress, which reflected a decline in the athlete's ability to cope with the training stimulus (Gomes et al., 2013). Further, running performance and $\dot{V}O_{2max}$ were reduced by 9.2 ± 7.7% and 4 ml·kg^{-1}·min^{-1} respectively following six weeks of intensified training in professional rugby players (Coutts, Reaburn, Piva, & Rowsell, 2007). The reduction in performance suggests the training program induced non-functional overreaching and was above the tolerance of improving fitness (Coutts, Reaburn, Piva, & Rowsell, 2007). Team sport athletes that experience sustained increases in week to week load without sufficient recovery may benefit from a de-load period, which elicits improvements in performance and reductions in muscle damage (Coutts et al., 2007). In this Australian football team, changes in monotony and strain did not affect the training-performance relationship. An explanation is our calculation of monotony and strain that was derived differently to the method which is traditionally used in the literature (Anderson et al., 2003; Aughey et al., 2015; Foster et al., 2001). Whilst the monotony and strain data in this study may be difficult to interpret, it should not deter practitioners from using such measures. Training monotony and strain, calculated with session RPE, have substantial relationships with match outcome in elite Australian football (Aughey et al., 2015) and injury and illness in women's basketballers (Anderson et al., 2003). The efficacy of monotony and strain derived in this way remains unknown, which warrants further research into the adaptability of such measures to the training load methodology like the one used in this study.

The acute:chronic ratio is commonly used to monitor if an athlete's acute workload is more or less than what the athlete is prepared for during the chronic period (Hulin et al., 2015). The acute:chronic ratio has largely been applied for predicting injury risk (Gabbett, 2016; Hulin et al., 2015), but it has yet to be used as a predictor of match performance. In terms of injury risk, an acute:chronic ratio between 0.8 to 1.3 is identified as the 'sweet spot', while ratios ≥ 1.5 represent the 'danger zone' (Gabbett, 2016). For comparison, in this case study across all positions, the mean ratio was ~1.0, which equates to the sweet spot for injury risk. While the effects were mainly *trivial*, match performance was generally higher near or below the mean, which suggests the 'sweet spot' for maximising match performance is similar to injury risk. Different sports, teams and load monitoring systems will likely have different training-performance relationships; therefore, these recommendations should be taken with caution and practitioners are urged to use a framework like that presented here to determine the ideal load in their cohort of athletes.

4.5 Conclusion

This study reinforces the importance of a load monitoring system in elite sporting environments. Due to the complex nature of training, quadratic modelling appears valuable when examining the training-performance relationship. Coaching and performance staff should avoid prescribing substantially high weekly and sustained increases in load during the competitive period of the season. Positional differences should be considered when planning and prescribing training loads across an entire Australian football season.

CHAPTER 5. A HOLISTIC TRAINING LOAD APPROACH TO ASSESS SOFT- TISSUE INJURY RISK IN ELITE AUSTRALIAN FOOTBALLERS

5.1 Introduction

Coaching and performance staff in elite team sport agree that injuries are detrimental to individual performance and team success (Hägglund et al., 2013). Multifactorial in nature, several risk factors play an important role in injury prevention (Drew & Finch, 2016). One important tool includes quantifying internal and external training load. Other individual risk factors such as the percentage of pre-season completed, history of previous injury and age can also influence training prescription (Colby, Dawson, Heasman, et al., 2017; Rogalski et al., 2013). The aim of training periodisation is maximising the stress incurred by training but allowing for adequate recovery. However, if the balance between training stress and recovery is incorrect, the risk of injury (particularly soft tissue) is increased (Gabbett & Ullah, 2012; Rogalski et al., 2013).

Training load can be viewed as the "vehicle" that drives an athlete toward or away from injury (Bourdon et al., 2017). External (Colby et al., 2014; Gabbett & Ullah, 2012) and internal (Cross et al., 2016; Rogalski et al., 2013) load measures are commonly used to examine the association between load and injury risk in team sport. In elite rugby league, players who completed more than 175 meters of high-intensity running (5 to 7 $m \cdot s^{-1}$) per session were 2.9 times more likely to sustain an injury that caused a player to miss a subsequent match (Gabbett & Ullah, 2012). In Australian football, larger one-week RPE load (> 1750 AU) substantially increased the risk of sustaining an injury during the season by a factor of 2.44 to 3.38 (Rogalski et al., 2013). Research investigating load and injury have utilised external and internal measures in isolation, however, no studies have applied a combination of external and internal parameters to examine this relationship in an elite team sport.

Several derivative measures of load calculated from daily RPE values are used for monitoring injury risk. Monitoring large accumulations and rapid changes in load from one week to the next are important injury risk factors (Rogalski et al., 2013). Rolling averages are used to analyse accumulated load over different periods (Drew & Finch, 2016), however, this approach fails to account for variations in load patterns and the declining nature of training stimulus over time (Menaspà, 2016). To address these issues, the use of exponentially weighted averages (EWMA) is proposed (Williams, Trewartha, et al., 2016). Despite the recent increase in attention, limited research exists investigating injury data and EWMA (Williams, Trewartha, et al., 2016). An absolute increase in RPE load from the previous week to the current week substantially increased the risk of injury for Australian footballers (above 1250 AU; factor of 2.58) and rugby union players (above 1069 AU; factor 1.58) (Cross et al., 2016; Rogalski et al., 2013). Training monotony and strain represents the day to day variability and overall stress of the training week respectively (Foster, 1998). In Australian football, there was little association between injury, monotony (r = 0.2) and strain (0.7) across the pre-season phase (Piggott, 2008). However, due to small sample size and only five injuries reported due to staff intervention, the statistical power of this study was diluted. Athletes deemed “at-risk” by medical staff but did not meet the criteria of an injury (any pain or disability suffered that restricted full participation in training) were prescribed alternate training sessions. Careful load monitoring every week is required to avoid residual fatigue and minimise the effect of training-related injuries (Gabbett, 2016; Rogalski et al., 2013). Such load measures derived from a combination of external and internal load have been used to assess changes in team sport performance (Chapter 4), however, no research exists examining the load-injury relationship.

Aspects of individual factors are likely to affect injury risk in team sports, but evidence in Australian football is limited. Periods of load intensification, such as pre-season, can increase the risk of injury (Jones et al., 2017). In rugby league, a 50 to 80% chance of soft tissue injury was reported when the pre-season weekly load was between 3000 and 5000 AU (Gabbett, 2010a). In elite Australian football, players who completed low (76 to 88 km; OR = 6.0) total distance in early pre-season and very low (< 108km; OR = 5.6) total distance in the late pre-season phase, were at a larger risk of sustaining an injury during the in-season (Colby, Dawson, Heasman, et al., 2017). Non-modifiable risk factors such as age and previous history of injury are important when considering an athlete’s risk of injury, however, practitioners can control this risk through careful training prescription. For example, at a given training load, older and more experienced Australian footballers were at a greater risk of injury compared to their younger counterparts

(Rogalski et al., 2013). Players with less than six year's experience (OR = 0.7) were at a lower risk than players with more than seven years when training load was above 1650 AU.

The first aim of this study was to examine the relationship between injury and load utilising a holistic load measure that includes a combination of external and internal parameters. The secondary aim was to determine the extent to which individual injury risk factors and derivative measures of load affect injury risk in an elite Australian football cohort.

5.2 Methods

Fifty-three male Australian footballers [mean ± standard deviation (SD): age 23.4 ± 3.2 y; height 188.3 ± 8.0 cm; body mass 88.6 ± 8.5 kg] participated in this study. Players were all registered to one Australian football club and competed in matches in the Australian Football League or Victorian Football League during the 2015 and 2016 seasons. The study was approved by the Victoria University Human Research Ethics Committee (HRE17-166), and all players provided written informed consent in accordance with the Declaration of Helsinki.

Injuries were recorded by the club's medical staff including head physician and physiotherapists, while the injury database was updated and maintained by the head physiotherapist. The dates of injury were documented along with the type and activity at the time of injury. An injury was defined as any injury that resulted in a missed match or missed full training session (Colby, Dawson, Peeling, et al., 2017; Orchard & Hoskins, 2007). Only soft-tissue non-contact injuries were included in this analysis as these injuries are considered preventable and influenced by the training measures included in this study (Gabbett, 2010a; Windt et al., 2016).

"On-legs" field training sessions were monitored with GPS units sampling at 10-Hz (Optimeye S5, Catapult Innovations, Melbourne). Physical activity profiles for each player included: total training and match volume (m), training and match high-velocity running volume (> 5.5 $m.s^{-1}$; m), match average speed ($m.min^{-1}$), count of match-high accelerations (> 3 $m.s^{-2}$) and decelerations (< -3 $m.s^{-2}$). The validity and reliability of GPS units are acceptable for these variables (Rampinini et al., 2015; Varley, Fairweather, et al., 2012). In-season training periodization comprised of one or two main "on-legs" field training sessions, two recovery sessions and one competitive match which were all included for the calculation of load.

Perceptual wellness diaries were completed by all players in the morning two days post-match to assist in monitoring the recovery process. Three main categories titled readiness to train, soft tissue status and overuse risk included 12 items, rated on a 10- point Likert scale ranging from 1 (feeling as bad as possible) to 10 (feeling as good as possible). Categories were chosen based on the experience and interests of conditioning staff as well as recommendations in the literature (Gastin et al., 2012; Montgomery & Hopkins, 2013). The sum of the individual items then provided a quantitative score of the overall perceived wellness for each player.

Weekly global load was derived by integrating external load (GPS parameters) and internal responses (wellness). Information detailing the weightings applied to variables can be viewed in Chapter 4. The following weightings were applied; total training volume/100, total match volume/100 × 1.5, training high-velocity volume/20, match high-velocity volume/10, match average speed/3, match high accelerations × 10, match high decelerations × 20, and wellness diary score × 3. After the weightings were applied, the variables are added together, and the resulting measure was expressed in arbitrary units.

Weekly load was then used to calculate additional derived measures of load. Smoothed load is an exponentially weighted moving average that accounts for the decaying effects of training load using a decay factor λ (lambda) (Hunter, 1986). The smoothed load for each week is calculated as λ × (the previous week's cumulative load) + (1 – λ) × (the smoothed load up to that point). The decay factor λ defines a time constant of 1/λ, which represents the period that contains ~2/3 of the total weighting in calculation of the smoothed load (Esmaeili, Stewart, et al., 2018). Smoothed loads were generated with λ values of 0.67 and 0.25 (time constants of 1.5 and 4 week) as previously described in Chapter 4.

Training monotony for each week was calculated by dividing the 3-week load rolling average by the SD of the 3-week of weekly load. Training strain was calculated by multiplying the monotony by the 3-week rolling average. Acute:chronic ratio was calculated by dividing the 1-week load by the 4-week rolling average (Hulin et al., 2015). Similarly, a smoothed acute:chronic ratio was derived in a similar fashion by dividing 1-week load by the 4-week smoothed load.

The pre-season phase started in November and continued until late March of the following year. Participation in pre-season training sessions for each player was recorded as a percentage. Player’s pre-season participation was quantified for “on-legs” field training sessions and all sessions which included resistance training. The in-season phase started in April and finished in September.

Two variables for days since a previous injury for each player was calculated using the injury database or previous seasons as required. The two variables were recorded as the number of days since any previous injury (contact and non-contact) and any soft tissue injury only. These variables started counting up from a player’s first-ever injury in the database and were reset to zero when a new appropriate injury was sustained. The variables started counting again when the player was participating in full training or matches.

The effects of training and other factors potentially affecting injury risk were modelled with univariate mixed models in the Statistical Analysis System (version 9.4, SAS Institute, Cary, NC). Training injuries and match injuries were analysed separately because our global load measure was monitored weekly. Therefore, the risk of injury during a match was predicted with the measure of training calculated for the week leading up to the match, whereas the risk of training injuries was predicted with the measure of training for the previous week, to avoid predicting the risk of an injury with training compromised by the injury.

The generalized linear mixed model (Proc Glimmix) (Schabenberger, 2005) with the complementary log-log link function was used to investigate the effect of factors affecting the risk (hazard) of soft-tissue injuries. Individual players who did not participate in field training sessions (training volume = 0) or matches (match volume = 0) were not available for injury; these sessions and matches were not included in the analysis, but a week of reduced training resulting from a previous injury was included in the analysis as a week in which a training injury could occur.

The effects of measures training load were analysed by assigning load measures in each season into quartiles for each player (Bartlett, O'Connor, Pitchford, Torres-Ronda, & Robertson, 2017; Hulin et al., 2015). This approach adjusted for changes in training between seasons. The thresholds were not individualised for relative training measures (acute:chronic ratio and smoothed acute:chronic ratio), as they are calculated as ratios. Training load quartiles were labelled very low, low, moderate, and high. The effects of individual characteristics were also analysed using quantiles, as follows: days since injury (very short, short, moderate, and long); pre-season completed (small, moderate, high, and very high); age (younger, middle, and older). Injury hazard (risk per player per week) was estimated in a model where season and the potential risk factor were the fixed effects. Player identity was included as a random effect to adjust for individual differences in players' risk of injury. An overdispersion factor was included in the model to allow for the proportion of injuries in any given week to be not perfectly binomially distributed. The lowest quantile for each risk factor was used as the reference group to derive the hazard ratio representing the effect on injury risk (Hopkins, Marshall, Quarrie, & Hume, 2007). The thresholds for the smallest important hazard ratio representing increase and decrease in injury risk were 1.11 and 0.90 respectively (Hopkins, 2010). Uncertainty in each effect was expressed as 90% confidence limits and as probabilities that the true effect was substantial using the following scale: <0.5%, most unlikely; 0.5% to <5%, very unlikely; 5% to <25%, unlikely, 25% to <75%, possibly; 75% to <95%, likely; 95% to <99.5%, very likely; >99.5%, most likely. The effect was deemed unclear when both the lower confidence limit was <0.90 and the upper confidence limit was >1.11 (Hopkins et al., 2009).

5.3 Results

One hundred and thirty-two soft tissue non-contact injuries were sustained over the study period. Of those injuries ninety-four occurred during a match and thirty-eight during training. Thresholds for all training measures and individual risk factors for each quantile are summarised in Table 5.1.

The risk per week (hazards) of training and individual measures on injury risk is presented in Table 5.2. The risk of sustaining an injury in a match was higher than training across all variables. The following quantiles for training measures were associated with the highest risk of a match injury: weekly load and acute:chronic ratio (very low) and 4-week smoothed load, 4-week differential load, strain, monotony and acute:chronic smoothed ratio (all low). For the individual risk factors, the highest risk of match injury was observed as follows: days since any injury (moderate), days since soft tissue injury (short), pre-season all (moderate), pre-season field (moderate) and age (older). Interestingly, a shorter period of smoothed load had a mirrored effect, such that a high and very low rate of change in load carried the same risk of sustaining an injury in a match.

A high to moderate level of training was generally associated with a reduced risk providing a protective effect against sustaining an injury during training. This effect was true for all training measures except monotony and strain (very low group having the lowest risk of injury). Completing a very high percentage of pre-season training and being an older athlete was associated with a low risk of training injuries.

Table 5.2 displays the individual effects of training and individual risk factors. Moderate accumulations of load over a shorter period (1.5-week smoothed) compared to very low accumulations resulted in a *very likely* reduction in injury risk during a game. A substantial decrease in injury risk was observed for the following training measures; high weekly load (*likely*), moderate acute:chronic ratio (*likely*), moderate acute:chronic smoothed ratio (*very likely*), very high pre-season completed all (*very likely*). On the contrary, an increase in training injury risk was revealed for high and low monotony (*very likely* and *most likely* respectively). All other effects were either unclear or *possible.*

Table 5.1. Mean thresholds of training measures and individual risk factors by quantiles for training and game injuries.

Derived measure	Level	Training injuries	Game injuries	Derived measure	Level	Training injuries	Game injuries
Weekly load	High	> 626	> 653	Acute:chronic ratio	High	> 1.27	> 1.28
	Moderate	550 – 626	594 – 653		Moderate	10.7 – 1.27	1.09 – 1.28
	Low	416 – 526	538 – 593		Low	0.93 – 1.06	0.99 – 1.08
	Very Low	< 416	< 538		Very Low	< 0.93	< 0.99
1.5-week smoothed load	High	> 590	> 616	Acute:chronic smoothed ratio	High	> 1.19	> 1.21
	Moderate	535 – 590	575 – 616		Moderate	1.05 – 1.19	1.08 – 1.21
	Low	419 – 534	530 – 574		Low	0.94 – 1.04	0.99 – 1.07
	Very Low	< 419	< 530		Very Low	< 0.94	< 0.99
4-week smoothed load	High	> 557	> 578	Days since any injury	Long	> 65	> 63
	Moderate	504 – 557	547 – 578		Moderate	32 – 65	35 – 63
	Low	431 – 503	504 – 546		Short	15 – 31	19 – 34
	Very Low	< 431	< 504		Very short	< 15	< 19
1.5-week differential load	High	> 82	> 103	Days since soft tissue injury	Long	> 161	> 156
	Moderate	9 – 82	22 – 103		Moderate	73 – 161	73 – 156
	Low	-57 – 8	-26 – 21		Short	31 – 72	35 – 72
	Very Low	< -57	< -26		Very short	< 31	< 35
4-week differential load	High	> 30	> 36	Pre-season completed (all)	Very high	> 94	> 92
	Moderate	7 – 30	14 – 36		High	81 – 94	78 – 92
	Low	-20 – 6	-4 – 13		Moderate	65 – 80	61 – 77
	Very Low	< -20	< -4		Small	< 65	< 61
Strain	High	> 6483	> 7940	Pre-season completed (field)	Very high	> 92	> 94
	Moderate	2881 – 6483	3942 – 7940		High	78 – 92	81 – 94
	Low	998 – 2880	1879 – 3941		Moderate	61 – 77	65 – 80
	Very Low	< 998	< 1879		Small	< 61	< 65
Monotony	High	> 11	> 13	Age	Older	> 27	> 27
	Moderate	5 – 11	7 – 13		Middle	23 – 27	23 – 27
	Low	2 – 4	3 – 6		Younger	< 23	< 23
	Very Low	< 2	< 3				

Table 5.2. Effects of the training measures and individual characteristics on game and training injury risk derived from a univariate mixed model.

Derived measure	Level	Training injuries	Game injuries	Derived measure	Level	Training injuries	Game injuries
Weekly load	High	1.1%, 0.46 (0.22 0.67)**	5.7%, 0.67 (0.41-1.09)*	Acute:chronic ratio	High	2.1%, 0.98 (0.51-1.89)	6.4%, 0.83 (0.50-1.36)
	Moderate	2.1%, 0.91 (0.5-1.64)	6.7%, 0.79 (0.5-1.24)		Moderate	0.9%, 0.46 (0.20-1.07)**	5.2%, 0.66 (0.39-1.12)
	Low	2.3%, 0.97 (0.55-1.71)	5.2%, 0.61 (0.38-0.98)*		Low	3.3%, 1.55 (0.84-2.87)	7.1%, 0.91 (0.56-1.48)
	Very Low	2.3%, reference	8.4%, reference		Very Low	2.1%, reference	7.7%, reference
1.5-week smoothed load	High	1.1%, 0.64 (0.29-1.37)	7.5%, 1.0 (0.63-1.59)	Acute:chronic smoothed ratio	High	2.6%, 1.53 (0.87-2.69)	4.7%, 0.65 (0.39-1.09)*
	Moderate	2.5%, 1.51 (0.81-2.79)	3.9%, 0.52 (0.31-0.89)***		Moderate	0.5%, 0.32 (0.14-0.76)***	6.6%, 0.92 (0.58-1.47)
	Low	2.2%, 1.32 (0.71-2.44)	6.9%, 0.93 (0.59-1.45)		Low	2.4%, 1.42 (0.80-2.52)	7.4%, 1.04 (0.66-1.64)
	Very Low	1.7%, reference	7.5%, reference		Very Low	1.7%, reference	1.7%, reference
4-week smoothed load	High	1.7%, 0.81 (0.44-1.53)	5.9%, 0.86 (0.52-1.42)	Days since any injury	Long	2.7%, 1.18 (0.68-2.05)	5.4%, 0.95 (0.56-1.60)
	Moderate	1.4%, 0.69 (0.36-1.33)	5.1%, 0.72 (0.44-1.20)		Moderate	1.4%, 0.63 (0.64-1.15)	8.5%, 1.51 (0.95-2.39)**
	Low	2.1%, 1.03 (0.59-1.82)	7.7%, 1.12 (0.71-1.75)		Short	1.6%, 0.73 (0.40-1.30)	6.0%, 1.06 (0.64-1.75)
	Very Low	2.1%, reference	6.9%, reference		Very short	2.2%, reference	5.7%, reference
1.5-week differential load	High	1.7%, 0.82 (0.43-1.55)	5.7%, 0.94 (0.56-1.58)	Days since soft tissue injury	Long	2.3%, 1.68 (0.88-3.20)	6.4%, 1.20 (0.72-1.98)
	Moderate	1.5%, 0.69 (0.35-1.34)	6.4%, 1.06 (0.65-1.73)		Moderate	2.4%, 1.71 (0.96-3.04)*	5.9%, 1.11 (0.67-1.85)
	Low	2.2%, 1.05 (0.59-1.88)	7.5%, 1.24 (0.78-1.98)		Short	1.7%, 1.20 (0.65-2.21)	7.9%, 1.50 (0.93-2.43)*
	Very Low	2.1%, reference	6.1%, reference		Very short	1.4%, reference	5.4%, reference
4-week differential load	High	2.3%, 0.93 (0.54-1.62)	6.0%, 0.90 (0.54-1.49)	Pre-season completed (all)	Very high	0.6%, 0.32 (0.12-0.89)***	5.9%, 0.83 (0.51-1.35)
	Moderate	1.4%, 0.57 (0.31-1.07)*	5.1%, 0.76 (0.45-1.26)		High	3.0%, 1.55 (0.76-3.16)	5.8%, 0.81 (0.49-1.34)
	Low	1.3%, 0.50 (0.27-0.94)*	7.9%, 1.21 (0.77-1.89)		Moderate	2.5%, 1.27 (0.62-1.62)	7.1%, 1.00 (0.63-1.59)
	Very Low	2.5%, reference	6.6%, reference		Small	1.9%, reference	7.0%, reference
Strain	High	2.6%, 2.04 (1.01-4.12)*	5.9%, 1.02 (0.59-1.75)	Pre-season completed (field)	Very high	1.2%, 0.59 (0.27-1.29)	6.8%, 0.98 (0.62-1.57)
	Moderate	2.3%, 1.80 (0.90-3.60)*	6.2%, 1.07 (0.63-1.80)		High	1.3%, 0.63 (0.30-1.30)	4.9%, 0.70 (0.42-1.17)
	Low	2.1%, 1.60 (0.79-3.23)	8.3%, 1.43 (0.88-2.33)		Moderate	2.6%, 1.30 (0.60-2.82)	7.1%, 1.03 (0.65-1.64)
	Very Low	1.3%, reference	5.8%, reference		Small	2.0%, reference	6.9%, reference
Monotony	High	2.6%, 4.11 (1.66-10.18)***	6.3%, 0.93 (0.55-1.55)	Age	Older	1.2%, 0.55 (0.25-1.17)	7.3%, 1.12 (0.74-1.69)
	Moderate	1.5%, 2.29 (0.89-5.92)	6.2%, 0.92 (0.55-1.52)		Middle	1.7%, 1.08 (0.56-2.07)	5.4%, 0.81 (0.52-1.26)
	Low	3.6%, 5.59 (2.36-13.24)****	7.1%, 1.06 (0.65-1.71)		Younger	2.8%, reference	6.6%, reference
	Very Low	0.6%, reference	6.8%, reference				

The effects are the hazards as a percentage and mean hazards (90% CI) expressed as risk per week for each quantile.
Likelihood for clear substantial effects: * possibly, ** likely, *** very likely, **** most likely. Likelihood for clear trivial effects: ^{0} possibly, ^{00}likely, ^{000} very likely, ^{0000} most likely. Results in bold represent effects clear at the 99% level; all others with superscript clear at 90%.

5.4 Discussion

The main findings of this study are: (1) a combination of external and internal load has potential to monitor injury risk in Australian football; (2) injury risk in matches is greater than training; (3) players in the moderate to high groups of training measures were at lowest risk of sustaining a match injury; (4) similar trends existed for training injuries; and (5) high levels of monotony and strain as well as short to moderate number of days since an injury increased the risk of sustaining an injury in a match or training.

This is the first study to utilise a holistic load measure that incorporates external and internal load to predict injuries in an elite team sport. The holistic measure proposed in this study may assist performance, coaching and medical staff when making multiple decisions to minimise injury risk for individual athletes. Decisions may include weekly training prescription or modifications, deciding on return to full training, and return to play criteria. Basing decisions on one measure can give practitioners confidence that both physical and perceptual aspects of load are covered. While this promising study is the first of its kind, more research is required to fully understand the complex interaction between global load and injury in an elite team sport.

A greater risk of sustaining an injury when competing in matches compared to training was observed. Australian football has evolved into a faster and more competitive game due to an increased focus on physical and tactical strategies (Bowen, Gross, Gimpel, & Li, 2016). Players covered an average total training distance of 6340 m and sprint distance (79 m) during the in-season phase (Colby, Dawson, Heasman, et al., 2017). In comparison, players covered an average total distance of 13439 m and 245 m of high-intensity running (> 75% of individual maximum speed) during games (Colby, Dawson, Heasman, et al., 2017) explaining the increased risk of injury during matches. This finding is supported by research in professional rugby union (Brooks, Fuller, Kemp, & Reddin, 2008). Whilst higher volumes of training did not increase the incidence of injuries, the severity and number of days missed due to match injury were substantially higher. High-intensity running is positively related to improvements in performance for elite Australian football teams (Mooney et al., 2011). However, if Australian footballers cover more than 1,453 m over 75% of their maximum speed in three weeks, they are 3.6 times more likely to sustain a soft tissue injury (Colby et al., 2014). Further, in another Australian football cohort, high levels of smoothed load over 14-days calculated by high-intensity running (> 4.17 m.s^{-1}) increased the risk of injury (hazard ratio 2.8; *most likely*) (Esmaeili, Hopkins, et al., 2018). The findings in this study support previous research (Colby et al., 2014; Esmaeili, Hopkins, et al., 2018; Gabbett & Ullah, 2012), highlighting the crucial challenge for performance and sport science staff to implement a training program that provides adequate recovery and minimising injury risk whilst preparing players to perform physically in matches.

It is important to note that inadequate training load also increased soft tissue injury risk in training and matches. Players transitioning back to full training or playing in matches following periods of lower training load likely explains this effect. This notion is supported by our finding that small increases (very low to low group) in smoothed load over longer periods (4-week) increased the risk of sustaining an injury. Additionally, a 10-day EWMA accounted for a large proportion (38%) of variance in injury risk of rugby union players indicating that cumulative load, is associated with accumulated fatigue (Williams, Trewartha, et al., 2016). Similarly, increases of injury risk were observed for 10-day and 14-day EWMA (internal load calculated by session RPE) in rugby union and Australian football respectively (Esmaeili, Hopkins, et al., 2018; Kara, 2013). Two-SD 10-day EWMA (ES = 1.32) and high levels of 14-day smoothed load (hazard ratio 2.2; *most likely*) increased the risk of injury. When accounting for the previous history of injury, the risk of injury is increased for the same training measure (hazard ratio 2.9*; most* likely) (Esmaeili, Hopkins, et al., 2018). Performance staff are recommended to prescribe, athletes returning from a soft tissue injury and transitioning back into training, a gradual accumulation in load to decrease the risk of injury. The second training measure which supports this finding is acute:chronic ratio and acute:chronic smoothed ratio. For both ratios, the low group had the greatest risk of injury indicating the athlete has completed less training in the current week then what was prescribed in the previous four weeks (Gabbett, 2016). In a study involving Australian footballers, training distribution played an important role in the return to play process (Ritchie, Hopkins, Buchheit, Cordy, & Bartlett, 2017). For example, two weeks before return to play following a lower-body injury, skill-based training was replaced with an increase in conditioning load such as running. Leading up to returning to play, weekly distance and high-speed running were reduced as the player transitioned back into the full training program (Ritchie et al., 2017). Training load management programs must monitor the quantity but also the type of training.

Individual non-modifiable and modifiable risk factors are crucial to load management and injury prevention practices. There was a substantial decrease in training injury risk when comparing players who completed a very high percentage of all pre-season sessions to players that completed a small percentage (hazard ratio = 0.32; *very likely*). The findings in this study are consistent with research in two other Australian football teams (Colby, Dawson, Heasman, et al., 2017; Murray et al., 2016). High and very high distance completed in early (OR = 0.6) and late (OR = 0.3) pre-season phases were associated with lower injury risk when compared to moderate distances. Additionally, injury risk was 1.9 times higher for players that completed less than 50% of pre-season training sessions compared to those that completed greater than 85% of training (Murray et al., 2016). A main focus of the pre-season phase is to improve fitness and build up players' load resilience with the ultimate aim of reducing the risk of injuries during the in-season (Colby, Dawson, Heasman, et al., 2017; Rogalski et al., 2013). It is important to the note, there is an association between increased injury risk associated and consistently higher load during pre-season (Gabbett, 2016; Windt et al., 2016). However, increasing pre-season participation can build a protective effect through greater strength and aerobic capacity, which offsets the increase in injury risk (Gabbett & Domrow, 2005; Hulin et al., 2015). We observed being an older athlete with an increased risk of match injury but a reduced risk of sustaining a training injury. Whilst our effects are unclear, previous research has highlighted the importance of age and experience in injury risk management (Esmaeili, Hopkins, et al., 2018; Rogalski et al., 2013). Age and experience can be considered confounding variables, as experience can only increase with age. One explanation for a reduced risk with training injuries is the number of year's experience in the AFL system exposing athletes to more physical conditioning (Young et al., 2005). The best 22 players in an AFL team are generally older and more experience and are known to be more successful (Chapter 3) highlighting their importance in team selection. However, the body's ability to adapt to training stimulus and recover from fatigue slows down as age and experience increases (Esmaeili, Hopkins, et al., 2018; Rogalski et al., 2013) suggesting older players may be playing with residual fatigue and consequently increasing their risk of injury in a match.

5.5 Conclusion

In conclusion, this study has shown the application of an innovative load management system to monitor injury risk in an elite team sport. In this first study to implement a combination of external and internal load to assess injury risk, performance and coaching staff would benefit from monitoring individual athlete’s load on a weekly basis. It is also important to consider individual risk factors when prescribing training during the season to minimize injury risk and maximize team success.

CHAPTER 6. GENERAL DISCUSSION, CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

6.1 Introduction

This thesis investigated multiple factors that affect team and individual performance and injury risk in elite Australian football. Whilst individual components of performance and injury risk have been broadly explored, there is a lack of evidence on how to integrate the sophisticated and multifactorial nature of a training program and monitoring system. This thesis builds on the understanding of the phenomenon of training, performance and injury risk. However, whilst this research is the first of its kind, the major findings regarding individuals can be compared to existing research. The implications of Chapter 3 have a large bearing on the seasonal training programme designed by performance and coaching staff, and in turn, affects individual performance and injury risk investigated in Chapter 4 and 5 respectively.

6.2 Fixture and team characteristics factors affecting match outcome

There are several factors thought to affect match outcome in elite Australian football. However, research has only investigated factors in isolation (Clarke, 2005; Kelly & Coutts, 2007; Richmond et al., 2007) or only involved one cohort (Gastin et al., 2013; Woodman & Pyke, 1991). Chapter 3 has built on this research by accounting for each factor and investigating match outcome across the entire AFL competition in a longitudinal analysis. It should be noted that individual team success could vary over a long period like the length of the database in Chapter 3. Therefore, this analysis carefully modelled each factor with random effects to account for differences between teams across multiple seasons. This approach supports the notion that individual differences between teams exist and whilst the results were not presented in Chapter 3, team success does change over time.

Chapter 3 provided further support to research indicating playing away is a disadvantage in multiple team sports (Clarke, 2005; Courneya & Carron, 1992). It appears home advantage is most strongly influenced by the team with a larger supporter base. The Australian football fixture involves regular travel during the season. Travel may include flights up to three hours long, crossing up to three time-zones and regular west-east travel for some teams. Findings of Chapter 3 identified travel as detrimental to team performance supporting research in Australian team sport (Bishop, 2004; Goumas, 2014) and Super Rugby (Lo, Aughey, Hopkins, Gill, & Stewart, 2019). Travel management strategies exist to assist coaching and performance staff to mitigate the effects of travel (Waterhouse et al., 2004).

The AFL takes into consideration several factors when designing the league fixture. Factors such as blockbuster/rival matches, attendance and TV ratings. As such, the number of days break varies for each team from week to week. The effect of days break between matches was trivial despite strong anecdotal belief in the Australian football community that day's break hinders performance. Chapter 3 is the first to investigate days break in Australian football and the findings in this study are consistent with research in rugby union (Robertson & Joyce, 2015). However, coaching and performance staff would agree the number of days break between a match has a large influence on how many training sessions are completed in each week. For example, a shorter turnaround of six days would generally leave room for one main training session allowing players sufficient recovery for the subsequent game. Performance staff need to consider the effect of days break on training prescription and subsequent team and individual performance.

The second element of Chapter 3 identified the importance of team characteristics in Australian football. The result that older teams have an advantage can be expected due to greater experience and skill level (Gastin et al., 2013). In another Australian football cohort, higher calibre players were substantially older than their lower calibre counterpart was (ES = 0.98, *moderate*) (Johnston et al., 2015). In each of these studies, the older players were identified as more tactically and technically skilful despite lacking a superior physical profile (e.g. lower average speed and total distance).

The effect of body mass on team success is slightly more complex. It could be hypothesised older players in a team are also the heavier players. However, by accounting for the confounding effects of body mass and age, the analysis in Chapter 3 identified this was not the case. Whilst the effect of a heavier player being advantageous suggests that a higher absolute body mass than your opponent may influence the chance of winning, the latter seems counterintuitive. Rather, one key focus of performance staff should be on the quality of strength and conditioning programs to balance improvements in strength and power whilst achieving optimal physical preparation (high ratio of lean muscle mass to fat mass).

Limitations of Chapter 3 included the use of online data provided to the AFL, other potential factors affecting match outcome and potential rule changes outside the data collection period. To research an entire competition, trust must be put into online data as well as a cross-checking protocol (checking online data against official statistics provided by the league e.g. AFL) like the one conducted in this study. The use of an online source to obtain league-wide data has been utilised in previous research to good effect (Robertson & Joyce, 2015). Future research may further dissect the current factors used in this study or investigate more factors (e.g. weather, time of match and crowd attendance) to further understand match outcome, which due to the number of factors already included in the study, were outside the scope of the current thesis. Despite the limitations, understanding the factors that can influence team performance across the whole competition should encourage coaching and performance staff to use this information for their cohort. Competition wide data, as opposed to case studies, provides deeper understanding and confidence to coaching and performance staff to build a successful team seasonal training programming. Chapter 3 successfully established macro-level determinants of team success in Australian football. Performance staff work with individual players within the team context, attempting to maximise individual physical preparation to play and succeed. Therefore, teams must have a way to determine if players are physically trained to succeed. Now, most use a combination of external and internal load measures, but few combine these into one measure. Therefore, Chapter 4 aimed to investigate the training-performance relationship using a global training load measure in elite Australian footballers.

6.3 A combination of external and internal load to assess performance in an elite team sport

One key aim of a successful training program is to improve weekly match performance through careful management of training load and recovery. Training program and monitoring systems are generally based on professional experience and anecdotal information. In elite sport, teams always seek to gain an advantage over the competition, therefore, strictly protect their intellectual property from other teams and the public. External and internal load quantification methods are well established in the literature; however, the load-performance relationship has predominantly been assessed using established measures (Gastin et al., 2013; Impellizzeri et al., 2006). The research in this thesis encourages practitioners to use a combination of external and internal load parameters in their monitoring systems to assist in decision making and ultimately enhance match performance.

First, results from Chapter 4 justified the use of a global training load measure for weekly individual monitoring to enhance match performance in Australian footballers. The sensitivity of changes in match performance encourages performance staff to take a global approach to calculate training load using a combination of external and internal load. A combination of load, especially those used in Chapter 4, provides a balance between an athlete's perception and quantifiable training (Bourdon et al., 2017). Utilising one measure can help simplify the difficult decision-making process for coaching and performance staff, identify information for training adaptation and ultimately improve subsequent match performance. It is important to note this weekly approach is suitable for sports that compete on a week-to-week basis such as Australian football. In sports such as football (soccer) or basketball, where up to two games can be played in seven days, daily monitoring may be more appropriate to assist performance staff. Whilst weekly monitoring may not be a suitable approach for every team, a global training load measure has the potential to be applied across different sports.

Enhanced match performance was observed when training measures were maintained near the weekly average. In elite team sport, whilst team-based training is common practice, individual prescription based on variable training response can help improve match performance (Gastin et al., 2013). An individualised approach is further supported in the literature considering endurance training (Bouchard et al., 1999; Scharhag- Rosenberger, Walitzek, Kindermann, & Meyer, 2012). Recommendations from Chapter 4 include training remains relatively near the mean (minor reductions or no change) in load measures to maximise match performance across playing positions. Players in different playing positions in conjunction with different physical attributes may be over and under-trained with a collective prescribed load, therefore impacting subsequent match performance. Performance staff needs to understand the requirements of different playing positions with their match demands to physically prepare athletes to compete. It is important to note the differences in weekly load values between positions; therefore, performance staff are recommended to monitor load within positional groups while considering individual differences. To maximise match performance during the competition season, individual players appear to benefit from consistent loading, interspersed with a de-load period. A de-load period may consist of a modified training session or rest in a given week in preparation for the upcoming match and can vary dependant on an individual athlete's level of load tolerance. Although training drills such as match simulation will naturally cater to the requirements of different playing positions, routine individual monitoring is the first crucial link for effective player management to enhance match performance across all positions.

Several derivative training load measures can be calculated to strengthen monitoring systems. Measures such as cumulative load, week-to-week changes, acute:chronic ratio, monotony, strain and exponentially weighted moving averages can be derived from session RPE values (Williams, Trewartha, et al., 2016). This research further adds to the knowledge in the elite team sport and monitoring training space informing of the usefulness of additional measures of load to assess changes in match performance. Chapter 4 also proves that such measures of load can be calculated using a combination of external and internal load.

Elite athletes are known to tolerate periods of high load, but it appears large accumulations (1 SD above the mean) in load during the competitive season leads to decreased subsequent Australian football match performance. To understand trends in load in the current week in comparison to previous weeks, practitioners have utilised a rolling average measure. However, rolling averages, fail to account for the decaying nature of load. That is, load in two weeks is assigned the same weighted importance as four weeks. The exponentially weighted moving average (smoothed load) accounts for the decaying nature of load. Differential load is calculated in a similar way to smoothed load, replacing the previous weeks load with the rate of change in load between the current and previous week. Results from Chapter 4 support the use of smoothed and differential load in monitoring systems to assess changes in subsequent match performance. Increases in the following training measures produced decrements in match performance: 1.5-week smoothed load and 4-week differential load. Preliminary results indicate a global training measure has the potential to be successful in calculating other derivative measures of load such as acute:chronic ratio, monotony and strain to assess match performance in Australian football. The findings above warn performance staff to tread carefully when prescribing cumulative increases in load or rapid changes over a 1.5 to 4-week period, which exceeds the amount for improved match performance.

The limitations of this study exist in the calculation of the global training load measure. It is crucial to note, this is a case study, having implications for practitioners when interpreting and comparing results. The chosen parameters were identified by performance staff based on the importance of each parameter to the cohort of athletes and the training program (see Chapter 4, section 4.3). Further, the weightings placed on the external and internal load variables in this study were chosen based on the impact of parameters on fatigue-inducing load, which may vary between different staff members and their principles and personal experience. It is also unknown what contribution each parameter makes to the effect of load on changes in match performance. The research in Chapter 4 provides the platform to establish this approach in other Australian football teams and team sports. To effectively use this approach, it is recommended that performance staff identify the load variables most important to their cohort of players. Training load variables can be identified using statistical modelling techniques such as principal components analysis and generalised linear mixed models. These analysis techniques have successfully selected training measures that had the largest associated with injury risk (Williams, Trewartha, et al., 2016) and the effect of training mode on measures of load (Weaving et al., 2014).

Overall, Chapter 4 adds to the importance of monitoring systems in an elite team sport. Load responses are relative to the individual athlete and their playing position urging coaching and performance staff to consider this for training periodisation. This study provides a platform for professional practitioners to implement their training monitoring systems to enhance match performance.

6.4 A holistic approach to assess soft tissue injury risk in Australian footballers

Monitoring training load as an injury risk factor is common practice (Taylor et al., 2012). It is widely accepted there are simultaneous and conflicting aims of a training program: improvements in performance and protection against injury. A monitoring system must be useful to achieve both aims of the training program whilst being easy to implement. Chapter 4 of this thesis successfully identified the effectiveness of a combination of external and internal load to assess match performance in elite Australian football. However, it is unknown, how this same training monitoring system can predict training and match injury risk in Australian footballers.

Injury is multifactorial, therefore, there are several contributing factors to injury risk such as previous injury history, age and the percentage of pre-season completed. Chapter 5 aimed to investigate these gaps in the literature.

Chapter 5 findings highlighted the potential application of a global training measure to predict training and match injury risk in elite Australian footballers. Performance staff have a difficult challenge of managing ~40 players in their cohort every week. Difficult decisions such as training modifications and return to training/playing criteria occur regularly. Simplifying the decision-making process by encompassing external and internal load parameters allows for informed decisions to assist in lowering injury rates.

This study identified several factors that increase the risk of soft-tissue injury. The risk of sustaining an injury in a match was higher than for training. Low levels of weekly load, acute:chronic ratio, 4-week smoothed load, 4-week differential load, strain, monotony and acute:chronic smoothed ratio was associated with the highest risk of match injury. The ability to utilise additional derivative measures of load to examine trends in load accounting for previous weeks provides performance staff with a comprehensive monitoring system. The effect of multiple risk factors further stresses the multifactorial nature of injuries and the importance to consider a thorough monitoring system in the injury prevention process.

The findings of Chapter 5 also emphasize the importance of individual factors in evaluating the injury risk of individual athletes. For example, the risk of injury was enhanced when athletes were older, recently experienced a soft tissue injury and completed a moderate percentage of pre-season. When profiling their athletes, performance staff are strongly encouraged to take into consideration the modifiable and non-modifiable injury risk factors identified in this study. Based on the current findings, performance staff are better placed to make informed decisions in injury prevention management when understanding the individual differences between their athletes.

One limitation of this study is analysing game and training injuries separately, reducing the number of injuries in each analysis. However, separate analyses allow practitioners to assess the effect of load on match and training related injuries in isolation. Whilst this study provides novel findings, it is important to note they are directly related to this sport and playing cohort. Care should be taken when comparing studies involving different teams with different load management strategies.

This thesis has provided a framework in understanding underlying factors of team success and the application of global monitoring systems to ensure a better application of training to improve match performance and reduce the risk of injury in elite Australian football.

6.5 Practical applications

The practical applications of this thesis are:

- Coaching and performance staff should focus on balancing adequate recovery from a match and implementing subsequent training from week to week.
- Whilst experience is an important factor in team success, coaches may benefit from exposing younger players to competition for future team planning.
- Strength and conditioning programs are crucial in developing strength and power whilst maintaining optimal relative body mass (high lean muscle mass vs. low fat mass).
- Load monitoring systems are a valuable component in an elite sporting environment.
- Playing positions and differences within those positions should be considered when planning and prescribing training load across an entire season.
- Utilising multiple training measures in the load monitoring system provides a comprehensive picture to assess changes in performance across playing positions.
- Monitoring Australian footballers over a macro cycle (one month using multiple periods) can assist performance staff in training periodisation and implementing recovery practices to improve player performance.
- The use of an innovative and holistic load management system has the potential to assess training and match injury risk in elite team sport.
- Understanding your cohorts training thresholds (i.e. very low to very high groupings) will provide context when evaluating injury risk in training and matches. It is important to note training thresholds will vary between teams, sports and playing levels.
- It is important to consider individual injury risk factors such as days since any or soft tissue

injury, percentage of pre-season completed and age when prescribing training during the season to minimise injury risk and maximise performance.

6.6 Conclusions

The specific conclusions of this thesis are:

- Australian football coaching and performance staff can use fixture and team characteristics to assist seasonal training periodization and team selection.
- Playing away, especially involving travel, should be strongly considered by coaching and performance staff given the negative impact on team success.
- Staff should focus on the structure of the training program rather than the number of days break alone.
- Coaching and performance staff should avoid prescribing substantially high weekly and sustained increases in load during the competitive season.
- Due to the complex nature of training, quadratic modelling is valuable when examining the training-performance relationship.
- From an injury prevention perspective, performance and sport science staff must monitor an individual athlete's load every week.
- The risk of a player sustaining an injury in a match is greater than training. Additionally, players that complete moderate to high levels of load had a reduced risk of match injury in this cohort.
- Completing a very high percentage of pre-season substantially reduced the risk of sustaining a training injury.
- Researchers should be cautious when analysing training and match injuries separately.

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APPENDIX 1

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH

You are invited to participate in this research project titled:

"Modelling training response and match performance in elite Australian football"

This project is being conducted by a student researcher Mr Brendan Lazarus as part of a PhD project at Victoria University/Collingwood Football Club under the supervision of Professor Andrew Stewart, Associate Professor Robert Aughey from the College of Sport and Exercise Science and Institute of Sport, Exercise and Active living (ISEAL).

The project will be assessing the following:

- The effect of training load measures on match performance in elite Australian football
- Quantifying the most commonly occurring movement sequences in elite Australian football training and matches
- The training-injury relationship in elite Australian football footballers

What will I be asked to do?

- Wear a Global Positioning System (GPS) device fixed into a vest or training jumper on the upper back during training
- Wear the same device in a specially designed pouch on the upper back of each playing jersey during matches
- Provide wellness scores at the beginning of each training session
- The above steps are the normal procedures that take place during each training session
- Allow previously collected training and injury data to be used in this research project

What will I gain from participating?

As a participant in this research project you will be contributing to the development of knowledge regarding the key aspects that influence match performance in elite Australian football. Ultimately, this research aims to understand the training process in a more sophisticated way which can then lead to improvements in individual player performance. This information will be utilised to contribute to the areas of monitoring training, athlete activity profile and individual and team performance in team sports.

How will the information I give be used?

All the information you provide to the research team (through personal details and the results of your participation in the project) will be kept strictly confidential. Data will be reported and presented internally to the High Performance Manager and Sport Scientist to be used appropriately. Data will also be reported and presented externally to the principal and associate investigators. These data may be presented through written publication, posters and conference presentations, however, all private information will be kept strictly confidential. Your personal information will not be passed onto any people or organisation other than the research team (details listed below).

What are the potential risks of participating in this project?

The associated risks with participation in the study are:

- Injury obtained from the Australian football matches, exercise tests or training sessions
- Feelings of intimidation when performing Australian football specific activity, and exercise tests in front of a group of observers
- Feeling pressured by others to participate in the research project

Access to medical staff including club doctor and physiotherapist will be available during all training sessions and matches.

How will this project be conducted?

Upon arrival you will be asked to read a description of the research project and sign a consent form. During field-based training sessions and matches you will be fitted with the GPS device. You will also be asked to provide wellness scores to the sport science staff prior to every training day.

Who is conducting the study?

Victoria University – Institute of Sport, Exercise and Active Living (ISEAL) and Collingwood Football Club.

Prof Andrew Stewart	**A/Prof Robert Aughey**	**Mr Brendan Lazarus**
Principal Researcher	Associate Researcher	PhD Candidate
Ph: (03) 9919 5200	Ph: (03) 9919 6329	Ph: 0421 948 496

Any queries about your participation in this project may be directed to the principal researcher 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, email researchethics@vu.edu.au or phone (03) 9919 4781 or 4461.

Please note that your participation in this project is voluntary, that is, it is not compulsory by virtue of your involvement with the club. Should you have any concerns about the conduct of this research project, please contact:

The Secretary

University Human Research Ethics Committee
Victoria University, PO Box 14428
Melbourne, 8001
Telephone no: (03) 9919 4781

Thank you for reading this statement and if you have any concerns or queries, please do not hesitate to contact Professor Andrew Stewart on 9919 5200. Alternatively the address for written correspondence is: Professor Andrew Stewart, College of Exercise and Sport Science, PO Box 14428, Melbourne, Victoria, 8001 Australia or andrew.stewart@vu.edu.au

Thank you for agreeing to assist us with our research.

[redacted]

Professor Andrew Stewart PhD
Professor of Clinical Exercise and Rehabilitation
Institute of Sport, Exercise and Active Living (ISEAL)
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