Examining the Demands and Load of Elite Rugby Union: Influence on Time-Loss Incidence Occurrence and Severity.

by

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Abstract

The studies described in this thesis were undertaken to examine the physical demands of elite Rugby Union and the subsequent impact on time-loss (injury and illness) incidence. Specifically, this thesis examined the demands of Rugby Union training and match play across two leagues of competition (Premiership and Championship) and between forwards and backs (the two main positional groups in Rugby Union). In addition, the thesis examined the effect of key performance indicators (such as tackles, contact carries and breakdown entries) and playing surface on time-loss incidence in matches; alongside the effect of training and match load on all time-loss incidences. Finally, the thesis also considered the severity (i.e. number of days lost) of time-loss incidences; specifically examining how training and match load affect the severity of time-loss incidences when they occur.

The first experimental chapter (Chapter IV) examined match and training demands associated with elite Rugby Union. Training and match load were assessed in eighty-nine players using both subjective (sRPE load) and objective (GPS) methods, alongside a host of key performance indicators in matches (tackles, tackle assists, tackles missed, contact carries, breakdown entries and contact events). These were compared between positions (forwards vs. backs) and league of competition (Premiership vs. Championship), using mixed effect models. Analysis revealed that backs covered a greater distance in training (by 704 m, $p<0.001$) and a greater distance (by 7.6 $m \cdot min^{-1}$, $p<0.001$) and high-speed running distance (by 1.22 $m \cdot min^{-1}$, $p<0.001$) in matches, compared to forwards. In matches, the forwards experienced greater contact demands (tackles: 78%; tackle assists: 207%; breakdown entries: 324%; contact events: 117%; all $p<0.001$) compared to backs. When comparing the Premiership and Championship, the number of tackles (53%, $p<0.001$) and tackles missed (35%, $p=0.001$) were greater, whereas contact carries (12%, $p=0.010$) and breakdown entries (10%, $p=0.024$) were lower, in the Premiership compared to the Championship. Overall, these findings suggest that the running demands of Rugby Union are higher in backs, whilst contact actions are higher in forwards; with further differences between the Premiership, where the defensive, tackle-centred demand was higher, compared to the Championship where the attacking, ball carrying, demand was increased.

The second experimental chapter (Chapter V) examined whether the key performance indicator variables examined in chapter IV had an impact on match injury incidence. The effect of each key performance indicator (tackles, tackle assists, tackles missed, contact carries, breakdown entries and contact events) on match injury incidence was assessed using mixed effect models. Overall match injury rate was 137.2 per 1000 h match exposure, with the most common site of injury being the head / face (21.7 per 1000 h) and knee (also 21.7 per 1000 h). The incidence of contact injuries was higher than non-contact injury incidence (119.4 per 1000 h vs. 17.8 per 1000 h, respectively). There was no effect of any of the key performance

indicators on match injury incidence, when quantified in absolute terms or relative to match duration of each individual player (all $p>0.05$). Therefore, in conclusion, monitoring such variables is not recommended for assessing injury risk. This may be due to every aspect of Rugby Union, from training to match play, requiring a high level of physical exertion and contact.

The third experimental chapter (Chapter VI) examined whether playing surface had an impact on match injury incidence. Three playing surfaces (grass, hybrid (some synthetic content) and fully synthetic) were modelled against match injury incidence. Injury incidence was more than twice as great on the hybrid playing surface (Odds ratio (OR) = 2.58, $p<0.001$) and synthetic playing surface (OR = 2.16, $p = 0.033$), compared to grass. When considering the modality of the injury (i.e. contact or non-contact), the odds of sustaining a contact injury on the hybrid surface (OR = 2.31, $p = 0.001$) and synthetic surface (OR = 2.19, $p = 0.049$) was over two times greater compared to grass. The odds of sustaining a non-contact injury was over four times greater on the hybrid surface compared to grass (OR = 4.18, $p = 0.028$). Despite the influence of playing surface on injury incidence, there were no differences in the severity of injury (minor severity: ≤7 d vs. major severity: ≥8 d) between time-loss incidences that occurred on each surface (all $p>0.05$). Therefore, these findings suggest that artificial surfaces increase the incidence of injury (both contact and non-contact injuries); yet there is no difference in the severity of the injuries that occur during matches on each surface.

The fourth experimental chapter (Chapter VII) examined the impact of match and training load on time-loss incidence occurrence, in both matches and training. sRPE load, distance and high-speed running distance were quantified using absolute values, the acute:chronic workload ratio (ACWR) and the exponentially weighted moving average (EWMA). The absolute match and training load variables provided the best explanation of the variance in time-loss incidence occurrence (sRPE load: $p<0.001$, Akaike information criterion (AIC) = 2936; distance: $p<0.001$, AIC = 3004; high-speed running distance: $p<0.001$, AIC = 3025). The exponentially weighted moving average approach (EWMA sRPE load: $p<0.001$, AIC = 2980; EWMA distance: $p<0.001$, AIC = 2980; EWMA high-speed running distance: $p=0.002$, AIC = 2987) also explained more of the variance in time-loss incidence occurrence than when the same variables were quantified using the acute:chronic workload ratio approach (ACWR sRPE load: $p = 0.091$, AIC = 2993; ACWR distance: $p = 0.008$, AIC = 2990; ACWR high-speed running distance: $p=0.153$, AIC = 2994). Overall, the absolute sRPE load variable best explained the variance in time-loss incidence occurrence, followed by absolute distance and absolute high-speed running distance. Furthermore, the EWMA approach was better at explaining the variance in time-loss incidence than when the same variables were calculated using the ACWR.

The fifth, and final, experimental chapter (Chapter VIII) examined the effect of each load variable on the severity (minor: ≤7 d lost; major: ≥8 d lost) of time-loss incidence. Overall,

57.0% (270) of all time-loss incidence had minor severity, with injuries split 49.5% (199) minor to 50.5% (203) major and illness 98.6% (71) minor and only 1.4% (1) major. The EWMA sRPE load variable best explained the likelihood of sustaining a major severity over a minor severity time-loss incidence ($p<0.001$, AIC = 436), followed by EWMA distance ($p = 0.001$, AIC = 437), absolute distance ($p = 0.004$, AIC = 440), absolute sRPE load ($p = 0.011$, AIC = 442) and ACWR sRPE load ($p = 0.024$, AIC = 443). Overall, these findings suggest that as match and training load increases, there is a concomitant increase in the likelihood of a major (compared to minor) time-loss incidence occurring. Furthermore, more of the variance in the severity of time-loss incidence is explained by the EWMA and absolute load quantified variables above the ACWR quantified variables.

Overall the results from this thesis provide novel evidence regarding the match and training demands of elite Rugby Union and how these demands relate to time-loss incidence risk. The key findings are that: (i) key performance indicators (such as the number of tackles made) did not affect injury incidence in matches; (ii) a synthetic playing surface increases injury incidence occurrence in matches; (iii) higher levels of match and training load increase time-loss incidence and the severity of the time-loss incidences; (iv) sRPE load appears to explain more of the variance in time-loss incidence and severity than GPS derived variables (distance and high-speed running distance); and, (v) the exponentially weighted moving average and absolute approaches to load quantification are better indicators of the change in time-loss incidence risk and severity than the acute:chronic workload ratio approach.

Keywords: Elite Rugby Union, Physical Demands, Match and Training Load, Acute:Chronic Workload Ratio, Exponentially Weighted Moving Average.

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Preface

Unless otherwise indicated by reference to published literature or acknowledgement, the work contained within this thesis is that of the author and has not been previously submitted for another degree to this or any other university.

Some of the work presented in this thesis has been published or presented as follows:

Published Papers

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Conference Presentations

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List of Abbreviations

3G – third generation
ACWR – acute:chronic workload ratio
AIC – Akaike information criterion
AU – arbitrary units
BIC – Bayesian information criterion
CI – confidence interval
EWMA – exponentially weighted moving average
glmer – generalised linear mixed effect model
GPS – global positioning system
HSR – high-speed running
KPI – key performance indicator
lmer – linear mixed effect model
OR – odds ratio
RFU – Rugby Football Union
RPE – rating of perceived exertion
sRPE – session rating of perceived exertion

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Chapter I
Introduction

Rugby Union is played by an estimated 5.3 million participants Worldwide. A highlight of the World Rugby Union calendar is a quadrennial World Cup. The last World Cup took place in Japan in 2019 and attracted over 857 million viewers; thus demonstrating the significance of the sport on the International stage (World Rugby, 2020). Rugby Union is an intermittent team sport where periods of near maximal and high-speed running demands are punctuated with aggressive contacts and collisions (Nicholas, 1997). Since the sport turned professional in 1995, the physical characteristics of the players have developed dramatically. Due to the financial rewards available following the professionalisation of the sport, club owners invested heavily in sport science support (such as physical conditioning and medical services), to ultimately increase the likelihood of being a successful team. By investing heavily in their assets (i.e. the players), the physiological characteristics (e.g. strength, speed, power) to the players improved, which, when combined with the demands of the sport, increased the frequency and intensity of both training and matches. This proliferation in physical demand, placed on the players in both training and matches, clearly has the potential to influence the likelihood of subsequent injury (and illness) occurrence (Lindsay et al., 2015).

Research studies exploring the demands and injury incidence rates of Rugby Union date back to pre-professionalism, with the injury incidence of International Rugby Union players reported to be 47.0 per 1000 h match exposure (Bathgate et al., 2002). In the years since the professionalisation of the sport, a steady increase in match injury incidence has been reported. For example, a match injury incidence of 74.0 per 1000 h match exposure was reported between 1996 and 2000 (Bathgate et al., 2002); and up to 218.0 per 1000 h match exposure reported between 2003 - 2008 (Brooks and Kemp, 2008). Occurring alongside this increase in injury incidence, there have also been improvements to injury reporting protocols (McCrory et al., 2018). However, an increase in injury incidence of the magnitude seen in the past 25 years is unlikely to be solely explained by changes injury reporting procedures; and thus, certainly warrants further investigation.

Alongside the increase in injury incidence, there has also been an increase in the running demands and contact/collision actions involved; around which the sport of Rugby Union is built. Investigations, firstly through time-motion analysis and then more recently with the use of microtechnology and global positioning systems (GPS), have objectively explored the demands of Rugby Union (Roberts et al., 2008; Lindsay et al., 2015). When investigating injury incidence in Rugby Union, it is important to consider the impact of key performance indicator variables (such as the number of tackles, contact carries and breakdown entries made). Research quantifying contact actions and their propensity to match injury incidence has been limited. The positional specific demands of International and domestic Southern Hemisphere competition have been quantified, however their influence on the likelihood of match injury has not been undertaken (Coughlan et al., 2011; Lindsay et al., 2015). Conversely, the sport specific scenarios (such as scrums, mauls, rucks) and their propensity to match injury have been explored at team level. However, this has not been explored at the individual player level, nor has the frequency with which these key performance indicators occur during a match.

Coinciding with the advancements in technology for tracking devices such as GPS (which are now commonly used to monitor training and match play in many elite athletes), the manufacture of ‘sports turf’ has also seen a significant change in the last 20 years. An ever-increasing number of competitive professional Rugby Union matches are taking place on either fully synthetic or hybrid (surfaces that contain some synthetic content alongside natural grass) playing surfaces. The versality and durability of these surfaces in varying climates make them ideal for multipurpose facilities, yet their health and injury ramifications are yet to be well explored (Duthie et al., 2013). Preliminary evidence suggests that there are no differences in match injury incidence between the synthetic and natural grass playing surfaces (Williams et al., 2016). However, previous research has not considered the hybrid surface (i.e. part synthetic, part natural grass), which Is now common in elite Rugby Union.

Another factor implicated in the incidence of injury (and illness) is load. Load has been defined and measured in numerous ways over a number of years in the sport science literature. A general definition would be a measure of the physiological stress placed on the human anatomy including, but not limited to, the neuroendocrine, immunological, cardiovascular and musculoskeletal systems (Halson, 2014). By way of its definition load can be assessed in many ways (e.g. external, internal, objective, subjective). For the purpose of this thesis, methods which could have practical utility within an elite sporting environment will be explored in more detail.

Research across team sports suggests that the accumulation of match and training load over a period of time contribute to injury and illness incidence (e.g. Foster et al., 1998; Rogalski et al., 2013; Hulin et al., 2014). Past research has suggested that the accumulation of unusually large volumes or unusually small volumes of load, in relation to an individual's typical exposure, poses an increased injury 'risk' (Blanch and Gabbett, 2016). This led to the creation of the acute:chronic workload ratio (ACWR), which for a number of years was frequently referenced within the literature and used practically across a number of sports in the applied setting. However, concerns regarding the methods by which the acute:chronic workload ratio was calculated were raised. Flaws such as mathematical coupling, and the disregard for the decaying nature of fitness and fatigue overtime, led to the proposal of the exponentially weighted moving average method of load quantification, a potentially more sensitive method of quantifying load. Load can also be measured via both subjective (i.e. how the athlete perceives the training session or match) and objective (i.e. the amount of work performed) methods (Halson, 2014).

It has been proposed that match and training load, quantified using the aforementioned methods (absolute, acute:chronic workload ratio, exponentially weighted moving average and cumulative weekly sums) has a relationship with time-loss incidence occurrence across a variety of elite level team sports. Research in Basketball (Anderson et al., 2003), Cricket (Dennis et al., 2003; Hulin et al., 2014), Rugby League (Gabbett and Domrow, 2007; Gabbett and Ullah, 2012), Australian Rules Football (Rogalski et al., 2013; Colby et al., 2014; Carey et al., 2017; Murray et al., 2017) and Association Football (Soccer) (Bowen et al., 2017) has demonstrated the influence match and training load can have on the incidence of injury and / or illness. Research exploring the potential relationship in Rugby Union has been limited, exclusively exploring subjective measures of load with restricted quantification methods (Cross et al., 2015). Furthermore, not only could the incidence of time-loss events be related to match and training load, but the severity (number of days unavailable for training and match selection as a result of an injury / illness) could also be affected. It is important to gain an understanding of the factors affecting both the incidence and severity of time-loss incidences, as these impact upon squad availability, which has been shown to be a key determinant of successful team performance (Carling et al., 2015; Williams et al., 2015). Ultimately, if a club can minimise the incidence and severity of time-loss incidences through appropriate load management protocols, they will increase their squad availability and thus, be more likely to be successful. This thesis will address these important research questions in elite Rugby Union.

The purpose of this research training was two-fold: for the candidate (an employee in the role of Sport Scientist at the Rugby Union club) to undergo the prerequisite study to fulfil the criteria and meet the requirements for the degree of Doctor of Philosophy; and for the collaborating establishment (the Rugby Union club) to a gain competitive advantage over teams competing in their league by practically applying the findings of this thesis. The research questions that were set at the beginning of the PhD were agreed between the Rugby club, the University and the candidate; with agreement reached on questions that would cover a novel area of research and also provide the Rugby club with solutions to practical problems, and ultimately a competitive advantage. Over the four-year research training process, the candidate advanced both the academic skill set aligned to a PhD process (e.g., study design principles, statistical analyses) and the practical skill set of working in an elite sporting environment.

The aims of this thesis are thus to gain a broad understanding of the demands faced by elite Rugby Union players in both training and matches, and to understand how these affect the occurrence and severity of time-loss incidences. Furthermore, this thesis will explore which match and training load quantification method best explains the variance of occurrence and severity of time-loss, alongside examining how the match key performance indicators and playing surface affect match injury incidence. Ultimately, the aim of the work presented in this thesis is to provide practitioners with a detailed understanding of the demands of elite Rugby Union and to provide information regarding the most effective method of load surveillance to minimise time-loss incidence and severity.

The following eight chapters document this work. *Chapter II* provides a review of the literature and describes what is currently known regarding the demands, match key performance indicator actions, playing surfaces, load, incidence and severity of time-loss incidence in both elite level team sports and, subsequently, with a focus on Rugby Union. The general methods used throughout the experimental chapters in this thesis are described in *chapter III*. The experimental chapters then describe and discuss the findings from studies designed to address the aims and objectives outlined above. *Chapter IV* provides an assessment of the training and match demands of elite Rugby Union. *Chapter V* examines how the key performance indicators (such as the number of tackles made) affect injury incidence during matches in elite Rugby Union players. *Chapter VI* examines another key determinant of injury incidence in elite Rugby Union matches; the playing surface. *Chapters VII* and *VIII* then investigate the influence of match and training load on the incidence (*chapter VII*) and severity (*chapter VIII*) of injury and illness in elite Rugby Union (with a focus on which load assessment and quantification methods best explain the variance in both occurrence and severity of time-loss incidences). *Chapter IX* then discusses the main findings of the five experimental chapters and draws overall conclusions, with the aim of having practical utility for practitioners working in not only Rugby Union environments, but also across elite sport teams.

Chapter II
Review of Literature

2.1 Definition of Terms

Throughout this thesis, a number of common terms relating to the overarching thesis title will be recurrently used. The terms include Rugby Union, training and match load, key performance indicators and time-loss incidence; these will be defined in this section.

2.1.1 Rugby Union

The sport of Rugby Union involves two teams, comprising of fifteen players each, competing over an eighty-minute period to accumulate points to ultimately determine match outcome (win, lose or draw). Rugby Union is a game composed of intermittent exercise where shorts periods of maximal or high intensity exercise are punctuated by lower intensity exercise or rest (Nicholas, 1997). Rugby Union is estimated to have over 5.3 million participants World-wide and is the national sport of New Zealand, Wales and Georgia (World Rugby, 2020). Rugby Union is played by men, women, boys and girls with players attracted due to its unique character-building values (World Rugby, 2020).

At domestic level in men's Rugby Union there are a number of countries with a professional Rugby Union league; the main competitions being the Gallagher Premiership (England), RFU Championship (England), Pro 14 (Ireland, Wales, Scotland, Italy and South Africa), Super Rugby (Australia, New Zealand, South Africa, Argentina and Japan), Top 14 (France), Mitre 10 (New Zealand), Currie Cup (South Africa), Top League (Japan), European Rugby Champions Cup and European Rugby Challenge Cup (countries that participate in the Six Nations). On the International scene there are 11 Tier 1 nations (New Zealand, South Africa, England, Wales, Ireland, Australia, France, Argentina, Scotland, Japan and Italy) and 12 Tier 2 nations (Georgia, Portugal, Romania, Russia, Spain, Canada, United States, Uruguay, Namibia, Fiji, Samoa and Tonga). There are a number of major International Rugby Union events, including a quadrennial World Cup (last held in 2019 in Japan, involving 20 nations and won by South

Africa), the Six Nations (England, Ireland, Wales, Scotland, France and Italy), the Rugby Championship (New Zealand, Australia, South Africa and Argentina) and the Pacific Nations Cup (Fiji, Samoa and Tonga). This demonstrates the sport's significance on the World stage (World Rugby, 2020). In England, the top two leagues of Rugby Union in England are classified as professional (Gallagher Premiership and RFU Championship), each comprising 12 teams (England Rugby, 2020).

Rugby Union matches last for 80 minutes in duration, two 40-minute halves, with the two teams competing to accumulate points by scoring tries, conversions, penalties and drop-goals (Duthie et al., 2003). A total of 23 players are available per team during a match, with 15 players from each side on the pitch at any one time. Each team is permitted to make a maximum of eight tactical substitutions during the 80-minute contest, with special dispensation allowed for injury to front row players and head injury assessment / blood injury to any player regardless of position. The men's game turned professional in 1995; eliciting a rapid growth in the physical profiles of the elite players. Research has since focused on the physiological and anthropometric characteristics of players along with the demands of competition. The sport is typically split into two main positional groups: forwards and backs. Forwards are typically heavier, taller and have a greater proportion of body fat compared to the backs although this stereotype has changed since the sport turned professional and the introduction of sport science, strength and conditioning and medical practitioners (Duthie et al., 2003). The playing positions can be broken down to their 15 constituent parts (forwards: (1) loose-head prop, (2) hooker, (3) tighthead prop, (4) left second row, (5) right second row, (6) blindside flanker, (7) openside flanker, (8) number 8; backs: (9) scrum-half, (10) fly-half, (11) left wing, (12) inside centre, (13) outside centre, (14) right wing and (15) fullback).

The women's game has attracted great interest in recent years following the introduction of the Tyrells Premiership 15's league in 2017; a £2.4 million investment by the Rugby Football Union (RFU) into the women's game over a three-year period (England Rugby, 2020). Furthermore, the RFU have started awarding full-time professional contracts to top senior England players with Saracens women and Worcester Warriors women paying players for the first time; a move which echoes the men's game transition to professionalism in 1995 (England Rugby, 2020).

2.1.2 Training and Match Load

Load has been defined in numerous ways over a number of years in the sport science literature. From its origins (according to popular legend) in the story of Milo of Croton (progressive overload training principles) to the multitude of definitions and quantification methods used across sport science practice today. A single sentence summary of load from all literature to date would be; a measure of physiological stress as a result of physical exertion placed on the human anatomy including the neuroendocrine, immunological, cardiovascular and musculoskeletal systems (Halson, 2014).

By way of its definition, load can be assessed in many ways and has the potential to provide rationality associated with the demands of a sport and time-loss incidence rates. The quantity of past research relating to load and its derivatives is beyond the capacity of this thesis, however several methods which could have practical utility within an elite sporting environment, will be explored in more detail.

2.1.3 Key Performance Indicators

The term key performance indicator (KPI) is the collective title for a host of variables specific to the actions carried out during a sporting activity, with this thesis focusing specifically on the actions during a Rugby Union match. Previous research has examined the number of scrums, mauls and lineouts (from a team / individual perspective) as well as a number of individual performance variables such as the number of tackles, breakdown actions and ball carries (Brooks et al., 2005a; Cunningham et al., 2018). A recent consensus statement on the descriptors of video analysis framework in Rugby Union provides definitions for a host of key performance indicator variables in Rugby Union (see Hendricks et al., 2020, for full details). In brief, sport specific scenarios, such as tackle event; an event where one or more tacklers (player or players making the tackle) attempted to stop or impede the ball carrier (player carrying the ball) whether or not the ball carrier was brought to the ground, are defined. This landmark publication will prove incredibly beneficial in future work, by providing a consistent framework for video analysis research in Rugby Union; aiming to end some of the ambiguities and inconsistencies used in previous publications (Coughlan et al., 2011; Quarrie et al., 2013; Lindsay et al., 2015).

2.1.4 Time-Loss Incidence

Time-loss incidence is defined as any physical complaint raised by an athlete which results in that individual be unable to complete training or match play for a period of greater than 24 hours (Fuller et al., 2007a). Time-loss incidence can be as a result of injury or illness, as both injuries and illnesses can prevent a player from participating in scheduled training or match play. The site, modality, session and severity of time-loss incidence are frequently referred to in previous literature when factors attributing to time-loss incidence occurrence have been assessed (e.g. Brooks et al., 2005a; Brooks et al., 2005b; Fuller et al., 2007b; Cross et al., 2016). These terms are defined as follows:

- the *site* of time-loss incidence refers to the physical location on the human anatomy where the time-loss incidence occurred (Fuller et al., 2007a), with previous research examining the most common sites of injury in training and matches (Brooks et al., 2005a; Brooks et al., 2005b);
- the *severity* of time-loss incidence; total number of days missed, from the date of injury/illness to date of return to full participation in training and availability for match selection (Fuller et al., 2007a);
- the *modality* of time-loss incidence refers to the underlying cause of the event (i.e. contact, non-contact or illness);
- the *session* of a time-loss incidence refers to the setting in which the injury occurred (i.e. match or training).

2.2 Demands of Rugby Union

Quantifying the physical demands of the elite Rugby Union has attracted a significant amount of research attention, particularly within the last 10-15 years (e.g. Roberts et al., 2008; Austin et al., 2011; Quarrie et al., 2013; Cunniffe et al., 2009; Coughlan et al., 2011; Cahill et al., 2013;

Lindsay et al., 2015; Campbell et al., 2018). A number of studies have attempted to quantify the physical demands of Rugby Union, predominantly through the use of time-motion analysis and global positioning systems (GPS), principally alongside the advancements in technology seen during this time. The following sections will examine the existing literature regarding the demands of Rugby Union, in matches and training, via both time-motion analysis and GPS techniques.

2.2.1 Match Demands

Table 2.1 details the nine studies that have considered the match demands of Rugby Union. Of these, four have used time-motion analysis (section 2.2.1.1) and five have used GPS (section 2.2.1.2).

Table 2.1. A review of the studies that have examined the match demands of Rugby Union.

Study Details		Methodology				Results
Author and Year	**Sport and Level of Competition**	**n**	**Running Demand**	**KPI Demand**	**Statistical Analysis**	
Duthie et al. (2005)	Male, elite, Rugby Union players (Super Rugby)	47	TMA	--	Independent samples t-test	Forwards ↑ 'work' compared to backs: 12:22 min:s vs. 4:51 min:s ($p<0.05$)
Roberts et al. (2008)	Male, elite, Rugby Union players (English Premiership)	29	TMA	--	ANOVA (post-hoc Tukey)	Total distance: backs ↑ forwards ($p<0.05$) High-speed running distance (5.0-6.7 $m{\cdot}s^{-1}$): backs ↑ forwards ($p<0.05$)
Hartwig et al. (2011)	Male, adolescent, Rugby Union players (Southern Hemisphere)	118	TMA	--	Mixed model ANOVA	Total distance; No difference between forwards and backs ($p>0.05$) High-speed running distance (>5.9 $m{\cdot}s^{-1}$); No difference between forwards and backs ($p>0.05$)
Austin et al. (2011)	Male, elite, Rugby Union players (Super Rugby)	20	TMA	--	ANOVA (post-hoc Tukey)	Total distance: inside backs ↑ front row forwards and outside backs ($p<0.05$) High-speed running distance: inside backs ↑ front row forwards ($p<0.05$)
Cunniffe et al. (2009)	Male, elite, Rugby Union players (Pro 14 and English Premiership)	2	GPS, 1 Hz GPSports SPI Elite	--	Descriptive (mean only)	Total distance: forward; 6680 m vs. back; 7227 m High-speed running distance (5.0-5.6 $m{\cdot}s^{-1}$): forward; 342 m vs. back; 292 m 'Sprinting' distance (>5.6 $m{\cdot}s^{-1}$): forward; 313 m vs. back; 524 m
Coughlan et al. (2011)	Male, elite, International Rugby Union players (Northern Hemisphere)	2	GPS, 5 Hz GPSports SPI Pro Elite	Notational analysis: tackles only	Descriptive (mean only)	Total distance: forward; 6427 m vs. back; 7002 m High-speed running distance (5.0-6.7 $m{\cdot}s^{-1}$): forward; 56 m vs. back; 74 m ($p<0.05$) 'Sprinting' distance (>6.7 $m{\cdot}s^{-1}$): forward; 3 m vs. back; 16 m ($p<0.05$)

Cahill et al. (2013)	Male, elite, Rugby Union players (English Premiership)	98	GPS, 5 Hz GPSports SPI Pro Elite	--	T-test and ANOVA (post-hoc)	Total distance: backs; 6545 m ↑ forwards; 5850 m ($p<0.05$) High-speed running distance (81-95% Vmax): forwards; 37 m vs. backs; 50 m ($p>0.05$)
Lindsay et al. (2015)	Male, elite, Rugby Union players (Super Rugby)	37	GPS, 10 Hz Catapult MinimaxX	Opta derived: tackles and tackle assists, contact carries, breakdown entries	Linear mixed effect models	Total distance: backs; 84.7 $m \cdot min^{-1}$ ↑ forwards; 77.3 $m \cdot min^{-1}$ ($p<0.01$) High-speed running distance (>7.0 $m \cdot s^{-1}$): backs; 1.30 $m \cdot min^{-1}$ ↑ forwards; 0.21 $m \cdot min^{-1}$ ($p<0.001$) Tackles and tackle assists: forwards; 0.15 $events \cdot min^{-1}$ ↑ backs; 0.11 $events \cdot min^{-1}$ ($p<0.01$) Contact carries: backs; 0.11 $events \cdot min^{-1}$ ↑ forwards; 0.08 $events \cdot min^{-1}$ ($p<0.05$) Breakdown entries: forwards; 0.33 $events \cdot min^{-1}$ ↑ backs; 0.13 $events \cdot min^{-1}$ ($p<0.001$)
Campbell et al. (2018)	Male, amateur, Rugby Union players (Southern Hemisphere)	32	GPS, 15 Hz GPSports SPI HPU	Notational analysis: tackles and breakdown entries	ANOVA (post-hoc Tukey)	Back 3 (6166 m) and half-backs (5760 m) ↑ total distance vs. front row forwards (4885 m) ($p<0.05$) Back 3 (400 m) completed ↑ high-speed running distance (>5.6 $m \cdot s^{-1}$) vs. all other positions (except centres) ($p<0.05$) Forwards completed ↑ breakdown entries compared to any backline player ($p<0.05$)

Key. KPI = Key Performance Indicator; TMA = Time-Motion Analysis; GPS = Global Positioning Systems; Vmax = individual player's maximum velocity; Hz = hertz; HSR = high-speed running.

2.2.1.1 Quantifying the Match Demands of Rugby Union through Time-Motion Analysis

The initial work exploring the match demands of Rugby Union was undertaken using time-motion analysis, a non-intrusive method of video analysis to gather information about players' movement patterns (e.g. time spent 'working', total distance covered and number of sprints; Duthie et al., 2005; Roberts et al., 2008). This technique allows researchers to quantify the type, duration and frequency of discrete movements that are commonly seen during intermittent team sports activities. These activities are most often classified as standing, walking, jogging, cruising, sprinting and static intense exercise (Deutsch et al., 1998). Using these classifications, the investigator must decide which activity the characteristics on the video relate and the duration of said effort. Time-motion analysis is therefore an incredibly time-consuming process and inherently prone to measurement error given the requirement for observer's knowledge, experience and focus of attention to detail.

Nonetheless, the first study to seek to quantify the movement patterns of domestic Rugby Union was undertaken using time-motion analysis in 47 Southern Hemisphere Rugby Union players (Duthie et al., 2005). The study cohort was split by position (forward and back) and the time spent completing 'work' (striding, sprinting, static exertion, jumping, lifting or tackling; for definitions see: McLean, 1992) was compared to the time spent at 'rest' (standing, walking and jogging) for the two positions. Results indicated that forwards completed greater amounts of work compared to backs across the course of an 80 min match (12 min 22 s ± 3 min 49 s vs. 4 min 51 s ± 1 min 16 s, respectively). These differences were due both to a higher frequency of work 'actions' and longer durations of work per occurrence (Duthie et al., 2005). Conversely, backs completed a greater number of strides (backs: 57 ± 22 vs. forwards: 39 ± 21) and a greater number of sprints (backs: 27 ± 9 vs. forwards: 11 ± 9). However, large differences were seen when comparing the static exertion actions (scrums, rucks and mauls) between the positional groups (forwards: 80 ± 17 vs. backs: 21 ± 11). Overall, whilst this study was the first in domestic Rugby Union to provide valuable information on the time spent at work and rest between the positional groups, the subjective nature of the analysis is a limitation.

Following the study of Duthie and colleagues (2005), a study using time-motion analysis, seeking to provide objective distance data on the match demands in 118 adolescent Rugby Union players from the Southern Hemisphere was undertaken (Hartwig et al., 2011). However, with the limitations surrounding the use of time-motion analysis (time and resource constraints), only 3 players per match were tracked. Subsequently the overall dataset only consisted of 53 individual match exposures, potentially explaining therefore why no difference in total distance or high-speed running distance (set at >5.9 $m{\cdot}s^{-1}$) between forwards and backs was seen (Table 2.1). Additionally, the sub-elite adolescent cohort means limited practical utility can be derived from the study to transfer the findings into the professional game.

However, Roberts and colleagues (2008) used computer analysis to automatically detect player movement speeds. At the time of publication (in 2008), microtechnology and global positioning systems were not available on the market, therefore, using a time-motion computer-based analysis approach was considered the gold standard technique to quantify the movement characteristics of team sports. Specifically, the player movements of 29 English Premiership Rugby Union players were captured by five distributed video cameras and then reconstructed on a two-dimensional plane representing the pitch (Roberts et al., 2008). Players were monitored during five leagues matches across the 2002-2003 and 2003-2004 seasons. To allow for inter-positional observations (Duthie et al., 2003), the players were divided into forwards and backs. Discrete velocity bands were used to examine the distance covered at each of the following speeds: standing/non-purposeful movement (0.0-0.5 $m{\cdot}s^{-1}$), walking (0.5-1.7 $m{\cdot}s^{-1}$), low-speed running distance (1.7-3.6 $m{\cdot}s^{-1}$), moderate-speed running distance (3.6-5.0 $m{\cdot}s^{-1}$), high-speed running distance (5.0-6.7 $m{\cdot}s^{-1}$) and very high-speed running distance (>6.7 $m{\cdot}s^{-1}$). For each individual player, data was collected during minutes 20-40 and 40-60 (i.e. the second and third quarters of the match) of the match. The distances were then normalised to 80 min to estimate the values for full (80 min) match. Results demonstrated that the backs covered more total distance than the forwards (6127 ± 724 m vs. 5581 ± 692 m), also covering a greater distance at higher speeds (i.e. at speed of 5.0-6.7 $m{\cdot}s^{-1}$; backs: 448 ± 149 m; forwards: 297 ± 107 m). The backs also covered a greater walking distance compared to the forwards (i.e. at speeds of 0.5-1.7 $m{\cdot}s^{-1}$; backs: 2351 ± 287 m; forwards: 1928 ± 234 m). However, there was no difference in the distances travelled within the other velocity bands between forwards and backs (low-speed running distance, moderate-speed running distance and very-high speed running distance).

Whilst this study provided a useful initial insight, the data were normalised to a full 80 min based on the data collected in the second and third quarters (20-60 min) of the matches. This approach is questionable given that the first 20 min and last 20 min are when the players are likely to be at their 'freshest' and most fatigued respectively, and thus their movement patterns may be significantly different to the observed period (20-60 min) of the match. The lack of relative speed classifications (i.e. all players performance was evaluated using the same absolute thresholds) is a further limitation given that the true maximum speeds will vary considerably between players (and likely between forwards and backs in particular). Therefore, utilising a relative approach to high-speed running threshold (e.g. greater than *x*% of an individual's maximum speed) may provide further insight into the positional demands associated with Rugby Union match play (Reardon et al., 2015; Gabbett, 2015). Additionally, it is not clear how this study dealt with replacements / substitutions during the 40 min of captured match play. Clearly, if a player was substituted during the data collection period this would have a profound effect on the distances they accumulated and should therefore be taken into consideration by applying a relative approach to match data (i.e. expressing distance as $m{\cdot}min^{-1}$, for example).

Using a similar time-motion analysis approach to that of Roberts and colleagues (2008), the physical running load demands of 20 Southern Hemisphere Super Rugby players was assessed (Austin et al., 2011). Players were split into four positional groups (front row forwards, back-row forwards, inside backs and outside backs). Video recordings were made using three cameras, with each camera filming just one player per match. The footage was subsequently analysed using hand-notations, with the discrete velocity bands determined subjectively (Duthie et al., 2005). Results suggested that front row forwards and outside backs covered significantly less distance than the inside backs, whilst the back-row forwards position was not statistically different to any of the other three positional groups for distance (Table 2.1). Additionally, high-speed running distances of 501 ± 163 m for the front row forwards, 918 ± 253 m for the inside backs and 558 ± 282 m for the outside backs were reported.

The high-speed running distances reported by Austin and colleagues (2011) are in stark contrast to the distances reported in International Rugby Union players (Quarrie et al., 2013). The movements and activities from 27 International matches were coded using semi-automated time-motion analysis. In contrast to the findings of Austin and colleagues (2011), high-speed running distance demands (for this study high-speed running was defined as 6.0-8.0 $m{\cdot}s^{-1}$), ranged from 170 ± 50 m for the props to 240 ± 50 m for the hooker position. Therefore, less than half of the 501 ± 163 m previously reported (Austin et al., 2011). These large variations reaffirm the concerns surrounding the use of time-motion analysis to assess the demands of Rugby Union, and in particular the potential positional differences in key variables of interest such as high-speed running distance. Furthermore, the time consuming and thus costly nature of time-motion analysis means it has very little practical utility as a day to day measurement tool.

2.2.1.2 Quantifying the Match Demands of Rugby Union through Global Positioning Systems

Given the limitations associated with time-motion analysis, the introduction of microtechnology in the late 2000s subsequently gained real interest and allowed researchers to objectively quantify the running demands of Rugby Union arguably much more accurately and quickly than the time-motion analysis methods used to this point. Of the six studies reviewed in Table 2.1, two were in amateur players from Southern Hemisphere competitions (Hartwig et al., 2011; Campbell et al., 2018), two were conducted in the English Premiership (Cunniffe et al., 2009; Cahill et al., 2013), one was in International Northern Hemisphere players (Coughlan et al., 2011) and one was conducted in elite Super Rugby players (Lindsay et al., 2015).

The initial work seeking to quantify the demands of Rugby Union through GPS was a case study which documented the demands of two elite Rugby Union players during an out of season competitive 80-minute match (Cunniffe et al., 2009). One forward (back row) and one back (fly-half) were selected to wear the GPS unit for the match. Total distance and distance per minute were recorded alongside the distance accumulated in discrete speed zones, including high-speed running distance (set at an absolute threshold of 5.0-5.6 $m{\cdot}s^{-1}$) and ‘sprinting’ (set at an absolute threshold of >5.6 $m{\cdot}s^{-1}$). The total distances covered by the two positions were 6680 m (66.7 m·min^{-1}) by the forward and 7227 m (71.9 m·min^{-1}) by the back. The forward completed more high-speed running distance compared to the back (342 m vs. 292 m, respectively), with the back accumulating greater distance whilst 'sprinting' (524 m vs. 313 m, respectively). However, given that the players were monitored in an out of season match, the relevance to in-season competitive play is questionable.

The second study exploring the demands of Rugby Union through GPS was again undertaken with a very small participant number (n = 2), but did examine an in-season International Rugby Union fixture (Coughlan et al., 2011). Similarly, a forward and a back were analysed with total distance and distances covered in discrete speed zones reported. At International level of competition, the back completed a greater amount of total distance, high-speed running distance and 'sprint' distance (total distance: forward: 6427 m vs. back: 7002 m; high-speed running distance [5.0-6.7 m·s^{-1}]: forward: 56 m vs. back: 74 m; 'sprint' distance [>6.7 m·s^{-1}]: forward: 3 m vs. back: 16 m). Whilst these initial studies (Cunniffe et al., 2009; Coughlan et al., 2011) provided a useful insight, due to the very limited sample size (n = 2 in both studies), these data must be interpreted with caution. The requirement for studies with a larger number of participants was clear, to allow statistical analysis to be undertaken and potential differences between the forward and back positions to be established.

Building upon this initial work, 98 elite players from eight English Premiership clubs were tracked using GPS during 44 competitive matches (Cahill et al., 2013). Results indicated that, on average, backs covered greater total distance compared to forwards (6545 m vs. 5850 m, respectively). However, no difference was observed for average high-speed running distance demand, set at 81%-95% of the individual players maximum velocity (forwards: 37 m vs. backs: 50 m). This was the first study to comprehensively address the demands of Rugby Union using GPS. However, whilst tackling the running load demands, a significant omission was that no mention or analysis of key performance indicator variables (such as tackles made) was undertaken. It is hypothesised that such contact actions are higher in forwards than backs, due to the nature of the game and the tendency for forwards to spend more time near the centre of the pitch where such contact actions take place (Duthie et al., 2003; Roberts et al., 2008). Therefore, these contact actions are potentially a key contributor to the overall demands of a Rugby Union match, and particularly the difference between forwards and backs.

Only two studies to date have considered the contact actions (e.g. the number of tackles made) as an element of the demands of Rugby Union alongside GPS running loads, both in Southern Hemisphere competition. The first, a study of 37 professional domestic Super Rugby players (Lindsay et al., 2015), used GPS to quantify running load and Opta statistics to quantify the contact actions (i.e. tackles and tackle assists, contact carries and breakdown entries). Whilst backs covered a greater distance and high-speed running distance, forwards completed more tackles, more tackle assists and entered more breakdowns compared to backs (Table 2.1). Conversely, backs completed a greater number of contact carries compared to the forwards. These findings suggest that the running load demands of Rugby Union are higher in backs, whilst the contact action demands are higher in forwards. Additionally, in a study of 32 Southern Hemisphere amateur grade Rugby Union players, with running load and contact action demands of Rugby Union (Campbell et al., 2018) collected data throughout a 19-week competition period was undertaken. Eleven randomly chosen players selected to wear a GPS unit during each match. GPS variables, total distance and high-speed running distance (set at >5.6 $m{\cdot}s^{-1}$) which were expressed in both absolute and relative to time formats along with key performance indicator variables (such as tackles, ball carries and breakdown entries) via notational analysis. For statistical analysis, players were split into six positional groups: back 3 (wing and fullback); centres; half-backs (scrum-half and fly-half); back row (flankers and number 8); second row; front row (props and hookers).

Results demonstrated how the back 3 and half-back positions covered greater total distances than the front row during match play and the back 3 completed more high-speed running distance during competitive matches than all other playing positions with the exception of centres (Campbell et al., 2018; Table 2.1). Similarly, centres completed more high-speed running distance than all forwards and the half-backs completed more high-speed running distance than the front row. However, it must be noted that no alterations were made for replacements with regards to total distance or high-speed running distance when expressed in their absolute form. With regards to the key performance indicator variables, the forwards completed more breakdown entries (ruck involvements) compared to any of the backs

(Campbell et al., 2018; Table 2.1). Therefore, the only studies to date to examine the contact action demands of elite Rugby Union have been done so in Southern Hemisphere Rugby, which may be different to English professional Rugby. Moreover, the Super Rugby season and more specifically the study presented by Lindsay and colleagues (2015) contains only 15 match exposures, this is less than half the length of a normal English Premiership / Championship season (England Rugby, 2020).

2.2.2 Quantifying the Training Demands of Rugby Union

Despite an abundance of literature examining the demands of Rugby Union match play, spanning both the elite and sub-elite levels (section 2.2.1), no investigation to date has attempted to analyse the training demands of Rugby Union at an elite level. As demonstrated in Table 2.2, only two studies have quantified the training demands of Rugby Union at any level, both examining sub-elite cohorts (Hartwig et al., 2011; Campbell et al., 2018).

Table 2.2. A review of the studies that have examined the training demands of Rugby Union.

Study Details			Methodology			Results
Author and Year	**Sport and Level of Competition**	**n**	**Running Demand**	**KPI Demand**	**Statistical Analysis**	
Hartwig et al. (2011)	Male, adolescent, Rugby Union players (Southern Hemisphere)	118	GPS 10 Hz GPSports SPI	--	Mixed model ANOVA	Total distance; No difference between forwards and backs ($p>0.05$) HSR distance (>5.9 $m \cdot s^{-1}$); No difference between forwards and backs ($p>0.05$)
Campbell et al. (2018)	Male, amateur, Rugby Union players (Southern Hemisphere)	32	GPS, 15 Hz GPSports SPI HPU	Notational analysis: tackles and breakdown entries	ANOVA (post-hoc Tukey)	Back 3 (4978 m), centres (5217 m) and half-backs (5259 m) completed ↑ total distance vs. back row (4173 m) and front row (4074 m) in training ($p<0.05$) Centres (2.9), back row (2.4) and second row (2.4) completed ↑ tackles vs. back 3 (1.1) in training ($p<0.05$)

Key. GPS = Global Positioning Systems; Hz = hertz; HSR = high-speed running.

Both studies which explored the potential differences in the training demands of Rugby Union (Table 2.2), also explored the match demands (section 2.2.1; Table 2.1). The first study to explore the potential positional demand differences in training, was in 118 adolescent Rugby Union players (Hartwig et al., 2011). Due to restrictions in the number of GPS units available, only 6 players per training session were monitored and due to the cohort being sub-elite adolescents, on-field training occurred only twice per week. Therefore, despite on the surface a large number of participants were involved (n = 118), there were a maximum number of 12 individual training sessions analysed per week; resulting in 161 individual training sessions in the overall dataset. No differences in the running load demands were seen between forwards and backs for distance or high-speed running distance (set at >5.9 $m{\cdot}s^{-1}$) in training (Table 2.2).

The second study to explore the training demands of Rugby Union was undertaken in a cohort of 32 amateur grade club Rugby Union players (Campbell et al., 2018). Players averaged two field training sessions per week, with data collected throughout the 19-week competition period. As explained in the match demands section (section 2.2.1), of the 32 players in the study, eleven randomly selected players were selected to wear a GPS unit during that week's training sessions, with key performance indicator variables (such as tackles, ball carries and breakdown entries) also recorded via hand notational analysis. GPS variables, total distance and high-speed running distance (set at >5.6 $m{\cdot}s^{-1}$) were expressed in both absolute and relative to time formats, and players were split into six positional groups: back 3 (wing and fullback); centres; half-backs (scrum-half and fly-half); back row (flankers and number 8); second row; front row (props and hookers). When assessing the differences in training demand, the back 3, centres and half-backs completed a greater amount of total distance compared to back-row and front row forwards (back 3: 4978 m; centres: 5217 m; half-backs: 5259 m; back row: 4173 m; front row: 4074 m), yet there was no difference in high-speed running distance between the positional groups (Campbell et al., 2018; Table 2.2). When comparing the key performance indicator variables between positional groups in training, the centres, back row and second row completed more tackles compared to the back 3 (centres: 2.9; back row: 2.4; second row: 2.4 vs. back 3: 1.1 tackles per session; Campbell et al., 2018; Table 2.2).

When comparing the two studies with regards to the running load demands, conflicting findings are seen (Hartwig et al., 2011; Campbell et al., 2018). In the study of adolescent Rugby Union, no difference in distance or high-speed running distance was observed between forwards and backs, whereas the study of amateur grade senior Rugby Union players reported differences in both distance and high-speed running distance demands between the positional groups. Therefore, questions still remain as to the potential differences in the positional demands of Rugby Union in training. Furthermore, neither of the two studies presented here were conducted within an elite cohort, as demonstrated by the limited number of training exposures (e.g. Campbell et al. (2018) presented data based on 19 weeks of competition; less than half of the length of a normal English Premiership / Championship season (England Rugby, 2020)). Nonetheless, future studies exploring the training demands would provide practical utility for practitioners by developing an understanding of the current demands and thus being able to incorporate changes to ensure that training demands are reflective of match demands wherever possible. This will enhance the likelihood that players are being adequately prepared for the physical demands they are subsequently exposed to on match days; with the ultimate aim of optimising performance and minimising the risk of injuries and illnesses occurring.

2.2.3 Summary of Match and Training Demands of Rugby Union

The papers discussed in this section of the literature review have examined the match running load and key performance indicator demands of Rugby Union, including both the early studies using time-motion analysis and then more recent studies using GPS. The consensus of the studies conducted to date is that, in matches the backs cover greater total and high-speed running distances compared to the forwards (Coughlan et al., 2011; Cahill et al., 2013), whereas the forwards undertake more contact actions (Lindsay et al., 2015). However, limitations surrounding the study design, statistical analyses and methods of data collation leave questions unanswered which subsequently warrant further investigation. Furthermore, a comprehensive examination of the training demands of elite level Rugby Union is required. No studies to date have made reference to the English Championship or compared the demands between the top two tiers of Rugby Union competition anywhere in the World (e.g. English Premiership vs. English Championship). Ultimately, such work would enable practitioners to develop a more detailed understanding of the demands of elite Rugby Union, and to ensure that adequate training protocols are in place to optimise performance and reduce the risk of injuries and illnesses occurring in both training and matches.

2.3 Match and Training Load and Time-Loss Incidence

A key objective of any applied practitioners working in elite sport is to reduce the likelihood of time-loss incidence occurrence. Inherently, by reducing time-loss incidence occurrence, squad availability for match selection remains high. It has been demonstrated in a number of professional sports, including Football (Carling et al., 2015) and Rugby Union (Williams at al., 2015), that success is inversely related to injury incidence, suggesting that player availability is a key determinant of success. One of the key factors affecting time-loss incidence is the management of match and training load (Blanch and Gabbett, 2016); the existing evidence for the relationship between match and training load and time-loss incidence, across sports, will be reviewed in the following section.

Assessing the potential relationship between match and training load and the incidence of time-loss events (injuries or illnesses) has been explored across a number of sports including Basketball (Anderson et al., 2003), Cricket (Dennis et al., 2003; Hulin et al., 2014), Rugby League (Gabbett and Domrow, 2007; Gabbett and Ullah, 2012), Australian Rules Football (Rogalski et al., 2013; Colby et al., 2014; Carey et al., 2017; Murray et al., 2017) and Football (Bowen et al., 2017). The subsequent section of this review will first consider techniques used to assess match and training load and then a host of different quantification methods applied to them. The effect that match and training load has on time-loss incidence across a number of aforementioned team sports will then be evaluated.

2.3.1 Methods to Assess Match and Training Load

For researchers and practitioners to examine the effect of match and training load on time-loss incidence, it is first important to understand the approaches taken to assess load. The overall goal of training is to elicit adaptation to ultimately drive performance, with the load exerted during a training session or match typically being classified as either external or internal (Kraemer et al., 2002; Halson, 2014).

Traditionally *external load* has been the cornerstone of most monitoring systems and is defined as the work completed by the athlete measured independently from their internal characteristics (Halson, 2014). An example of this for cycling would be the mean power output sustained over a set period of time (i.e. 400 W cycling power output over 30 min period). External load provides an understanding of the absolute amount of work completed and the capabilities and the capacities of the athlete (Halson, 2014).

Conversely, *internal load* considers the relative physiological and psychological stress that completing a training session or match, for example, places on the athlete. It is therefore suggested that internal load may be more valuable when assessing match and training load and subsequent adaptation (Halson, 2014). An example of internal load monitoring is heart rate. The use of heart rate monitoring during exercise is based on the linear relationship between heart rate and oxygen uptake during steady-state exercise (i.e. mean heart rate of 152 beats$\cdot$min^{-1} during a 10 km steady-state WattBike session). It is important to note that both external and internal load provide crucial information and therefore a combination of both may prove to be the most beneficial during the load monitoring process (Halson, 2014).

Another aspect of the load monitoring process that works in conjunction with the external/internal load profile, is whether the particular variable of interest is objective or subjective. Objective measurements, such as distance and heart rate are not affected by the way that the athlete perceives the training session or match (Borresen and Lambert, 2008). Conversely, subjective measurements refer to the data derived from the athlete’s personal feelings, perspectives and opinions of a training session or match (Borresen and Lambert, 2008). Previous work has demonstrated the usefulness of objective and subjective measures of load. Objective, GPS-derived measures of load have been shown to be related to the risk of sustaining injury in elite Australian Rules Footballers (Murray et al., 2017) and subjective, sRPE load has been shown to explain the risk of injury, again in Australian Rules Footballers (Rogalski et al., 2013).

Examples of these types of load measures are shown in figure 2.1:

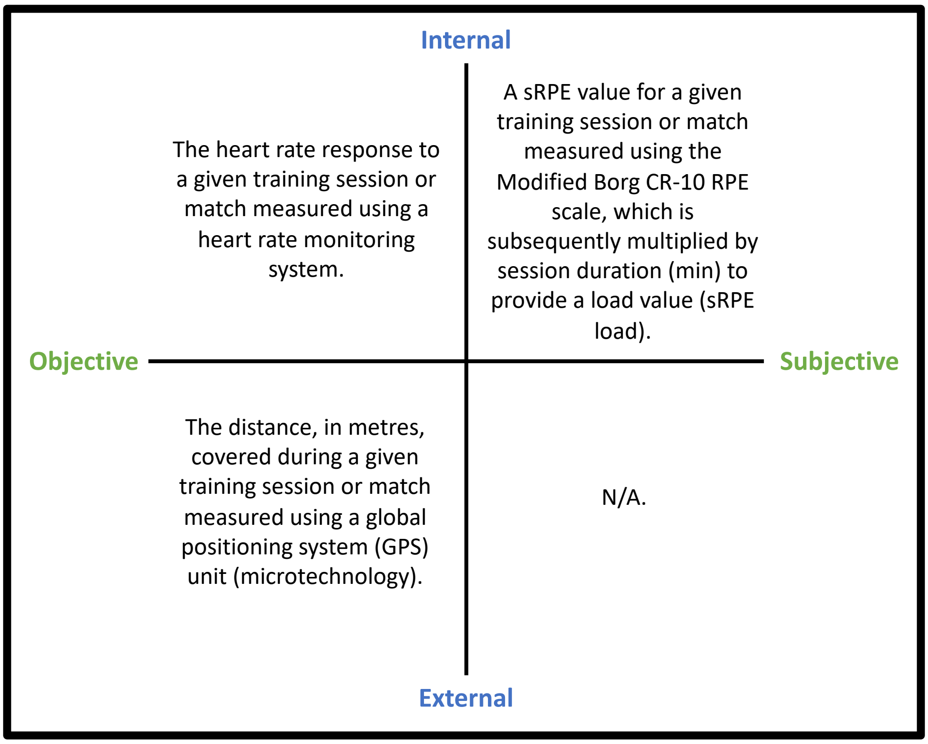


Figure 2.1. Examples of methods used to assess load; external, internal, objective and subjective.

The study design characteristics and methods used to assess load in ten studies that have been conducted to explore the potential relationship between match and training load and time-loss incidence are demonstrated in Table 2.3. Of the ten studies, three studies exclusively explored the relationship between internal subjective derived load and time-loss incidence and five studies solely explored the relationship between external objective derived load and time-loss incidence. The two remaining studies used a combination of internal subjective and external objective derived load and time-loss incidence (Table 2.3). It is interesting to note that no study to date has used internal, objective methods, such as heart rate, to consider the relationship between match and training load and time-loss incidence in any elite team sport.

Table 2.3. A review of the study design characteristics of the match and training load and time-loss incidence studies in all sports.

Study Details				Methodology		
Author and Year	**Sport**	**Level of Competition**	**Participants**	**Method of Assessment**	**Load Variables**	**Injury / Illness Reporting**
Anderson et al. (2003)	Basketball	Collegiate	Female; n = 12	Internal, subjective	sRPE load	Self-report questionnaire All injuries and illnesses
Dennis et al. (2003)	Cricket (Fast Bowlers)	Elite	Male; n = 90	External, objective	Number of balls bowled	Club's medical staff 'Bowling' injuries only
Gabbett and Domrow (2007)	Rugby League	Elite	Male; n = 183	Internal, subjective	sRPE load	Club's medical staff All injuries
Gabbett and Ullah (2012)	Rugby League	Elite	Male; n = 34	External, objective	GPS	Club's medical staff Non-contact, lower body soft-tissue injuries only
Rogalski et al. (2013)	Australian Rules Football	Elite	Male; n = 46	Internal, subjective	sRPE load	Club's medical staff All injuries
Colby et al. (2014)	Australian Rules Football	Elite	Male; n = 46	External, objective	GPS	Club's medical staff All injuries
Hulin et al. (2014)	Cricket (Fast Bowlers)	Elite	Male; n = 28	Internal, subjective and external, objective	sRPE load and Number of balls bowled	Club's medical staff Non-contact injuries only

Carey et al. (2017)	Australian Rules Football	Elite	Male; n = 53	Internal, subjective and external, objective	sRPE load and GPS	Club’s medical staff Non-contact, time-loss match injuries only
Bowen et al. (2017)	Football	Elite Youth	Male; n = 32	External, objective	GPS	Club’s medical staff All injuries
Murray et al. (2017)	Australian Rules Football	Elite	Male; n = 59	External, objective	GPS	Club’s medical staff Non-contact, time-loss only

As demonstrated in Table 2.3, the principle methods used to assess match and training load across these studies are the internal subjective method of sRPE load and the external objective GPS-derived variables.

2.3.1.1 sRPE Load

The requirement for an easy to administer method of load assessment led to the proposal and creation of the session RPE (sRPE) load metric (Borg et al., 1987). sRPE is determined by using the modified Borg CR-10 scale (Figure 2.2; Borg et al., 1987), where the athlete / participant provides a session rating of perceived exertion (RPE) which is then multiplied by the session duration (in minutes), to give the overall sRPE load in arbitrary units (AU). This rating is obtained within 30 min of the end of the training session and/or match, in line with recommendations (Kraft et al., 2014). For example, if an athlete completes a 75-minute session and provides a rating of 7 on the Borg CR-10 scale:

$$\text{sRPE load} = \text{RPE} \times \text{session duration} = 7 \times 75 = 525 \text{ AU}$$

The sRPE method of load assessment is used commonly across multiple sports and numerous levels of competition (e.g. Anderson et al., 2003; Gabbett and Domrow, 2007; Rogalski et al., 2013; Carey et al., 2017). One of the key advantages of the sRPE load method is the relative ease at which data can be collected from large cohorts of athletes, in a cost-effective manner, in comparison to other methods (e.g. GPS which requires high technical expertise and expensive equipment). This likely contributes to why the sRPE load method is seen as an invaluable monitoring tool across all levels of sport (Haddad et al., 2017).

RPE (Rating of Perceived Exertion).	
Rating.	**Description.**
0	Nothing At All.
1	Very Light.
2	Fairly Light.
3	Moderate.
4	Somewhat Hard.
5	Hard.
6	
7	Very Hard.
8	
9	
10	Very, Very Hard (Maximal).

Figure 2.2. The modified Borg CR-10 rating of perceived exertion (RPE) scale.

2.3.1.2 GPS-derived Variables

A GPS device can provide researchers and practitioners with a host of external objective measures of load as demonstrated in section 2.2 (demands of Rugby Union). These include the total distance covered, the distance covered within discrete velocity bands, and the number of accelerations / decelerations completed by an athlete / participant during a training session or match. As demonstrated in Table 2.3, following its establishment in the early 2010's, almost all studies seeking to explore the relationship between load and time-loss incidence have utilised GPS devices, to provide an external, objective measure of match and training load (Gabbett and Ullah, 2012; Carey et al., 2017; Bowen et al., 2017; Murray et al., 2017). Furthermore, the capability for GPS units to provide live feedback during training sessions and matches means its practical utility for practitioners during rehabilitation protocols following injury are unrivalled (Coughlan et al., 2011).

2.3.2 Load Quantification Methods

In addition to the variety of methods used to assess match and training load (section 2.3.1), research exploring load monitoring in sport has also quantified load in multiple ways. Such methods have ranged from the simplest form of absolute match and training load (e.g. total distance covered in m), to the complex mathematical equations used in the training impulse, acute:chronic workload ratio and exponentially weighted moving average approaches. These methods will be discussed in the following sections, detailing their calculation methods and their potential utility and limitations, for researchers and practitioners, as a load monitoring tool.

2.3.2.1 Absolute Load

The most basic level of load quantification is to utilise the absolute load derived from the method in question. For example, the average power output during a cycle ergometer trial (e.g. 400 W), the total distance covered during a training session or match (e.g. 4750 m), the average heart rate during steady-state exercise (e.g. 158 beats·min^{-1}) or the daily sRPE load (e.g. 525 AU). These absolute load values can subsequently be modelled against performance or injury and illness incidence to explore the potential relationships between load and stress response. In fact, table 2.4 demonstrates that the absolute load variables are the most commonly used to assess the effect of load on time-loss incidence, being used in 9 out of the 10 studies.

2.3.2.2 Training Impulse

The first attempt made to quantify the load experienced by an athlete was using the training impulse (Morton et al., 1990). The quantification of training was measured using two variables (duration and concomitant heart rate) which were combined in a linear difference equation to predict performance levels appropriate to the intensity of the training being undertaken.

The training impulse was calculated by assessing each exercise segment of training during which the heart rate was relatively constant. The product of each segment and the concomitant fractional elevation in heart rate provided a quantitative assessment of training volume. Therefore, training may be quantified as the area under the curve represented by the following equation:

$$w(t) = (\text{duration of exercise}) * ((HR_{ex} – HR_{rest}) / (HR_{max} – HR_{rest}))$$

w(t) = Training impulse (TRIMP)

HR_{ex} = Average heart rate during the exercise

HR_{rest} = Resting heart rate

HR_{max} = Maximal heart rate during the exercise.

There are then numerous weighting factors which are applied depending upon the sex of the athlete, relative intensity of the session and time decay constants (a full review of this method is beyond the scope of this thesis; for a review see Morton et al., 1990). However, the main limitation of the training impulse equation is its requirement for steady-state heart rate measurements. Ultimately, this limits its practical utility in any activity where a steady state heart rate is not achieved (e.g. team sports). Consequently, researchers continued to seek a more well-rounded, practical, daily load monitoring tool (Borresen and Lambert, 2008).

2.3.2.3 Acute:Chronic Workload Ratio

In 2016 the study of the load : injury relationship in sporting populations changed dramatically, when Blanch and Gabbett (2016) introduced the acute:chronic workload ratio (ACWR); proposed as a practical, daily, load monitoring tool. Building on earlier work (Calvert et al., 1975; Morton et al., 1990), a model was produced comparing the acute load (the load that had been performed in the past 7 days) and the chronic load (the load that had been performed in the past 28 days). The size of the acute load in relation to the chronic load provides a ratio score used to assess injury risk / incidence and performance. An acute:chronic workload ratio of 0.5 suggests that an athlete has completed only half as much work, on average, in the past 7 days as they had, on average, in the past 28 days. Conversely, an acute:chronic workload ratio of 2.0 would suggest that an athlete has completed twice as much work, on average, in the past 7 days as they had, on average, in the past 28 days. A worked example of the acute:chronic workload ratio:

Athlete A has run an average of 2000 m per day in the last 7 days and an average of 2500 m per day in the last 28 days:

$$\text{ACWR} = \frac{\text{Load in the past 7 days}}{\text{Load in the past 28 days}} = \frac{2000}{2500} = 0.8$$

Athlete B has run an average of 4750 m per day in the last 7 days and an average of 2375 m per day in the last 28 days:

$$\text{ACWR} = \frac{\text{Load in the past 7 days}}{\text{Load in the past 28 days}} = \frac{4750}{2375} = 2.0$$

Following the inception of the acute:chronic workload ratio as a method of load monitoring between 2014-2017, multiple studies assessed the potential load : injury relationship (e.g. Hulin et al., 2014; Carey et al., 2017; Bowen et al., 2017; Table 2.4). However, a number of concerns regarding the acute:chronic workload ratio approach have been published (e.g. Menaspa, 2017; Williams et al., 2017; Lolli et al., 2017; Lolli et al., 2018).

The initial concerns surrounding the acute:chronic workload ratio was made by Paolo Menaspa (2017), in a commentary in the British Journal of Sports Medicine, which focused mainly on the rolling average approach used in the original model (Blanch and Gabbett, 2016). Menaspa raised concerns around the fact that averages overlook variations within set periods of time and obscure overall load patterns. Figure 2.3, taken from the commentary, demonstrates the potential flaws in the rolling average approach to load quantification.

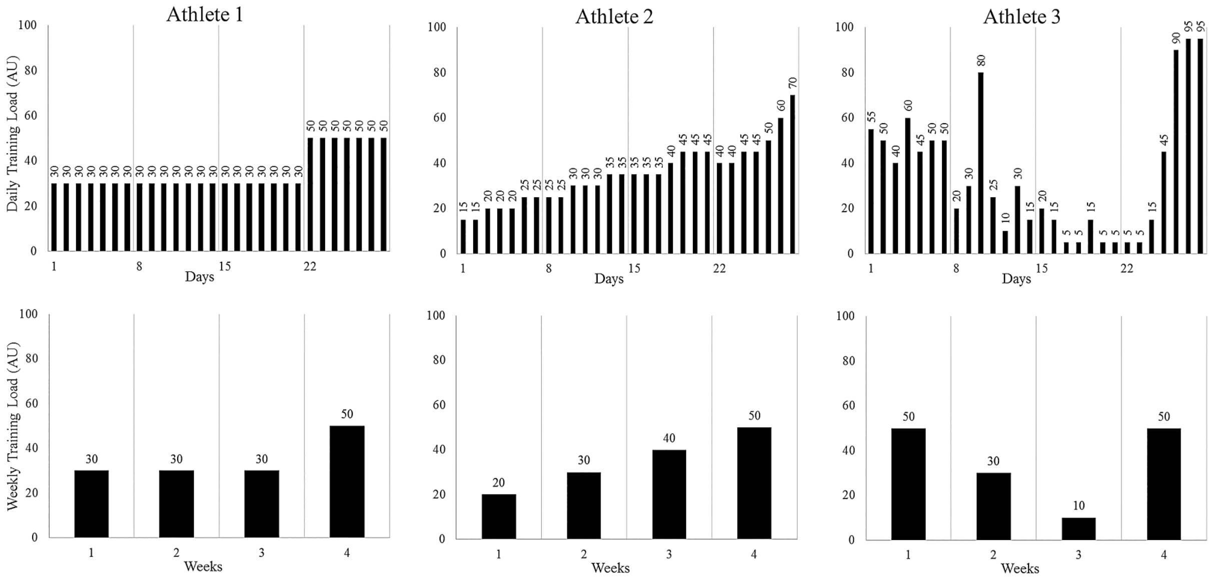


Figure 2.3. The visual description of the limitation of rolling average approach to load quantification (taken from Menaspa, 2017).

Fictitious athletes (1, 2, 3) have identical acute (last 7 days) and chronic (last 28 days) average loads (acute 50 AU; chronic 35 AU), therefore presenting an identical acute:chronic workload ratio (ACWR = 1.43). However, as can be seen in Figure 2.3, the athletes have very different daily variations and chronic load patterns. Furthermore, the averaging of load of over a set timeframe (i.e. 7 or 28 days) does not account for exactly when the stimulus occurred and subsequently the effect of training stimuli declining overtime (Hawley, 2002). Therefore, the acute:chronic workload ratio approach would suggest that the load accumulated the day before an event/injury is equal to that in a session occurring 28 days previous; challenging the conventional wisdom that fitness and fatigue decay overtime. Given these criticisms, it was hypothesised that a non-linear approach to load quantification might be better suited to identifying the likelihood of time-loss incidence occurrence.

Additional concerns surrounding the acute:chronic workload ratio as a method of load quantification were raised in two editorials by the same research group, specifically relating to the mathematical underpinning of the acute:chronic workload ratio (Lolli et al., 2017; Lolli et al., 2018). As detailed in section 2.3.2.3, the standard acute:chronic workload ratio is the load accumulated in the most recent 7-day period (acute) divided by the longer term 28-day period (chronic). Whilst it is important for the numerator and denominator of any ratio to be correlated through biological mechanisms, one aspect of the acute:chronic workload ratio calculations are that the acute load also constitutes a substantial part (25%) of the chronic load (Pearson, 1897). This mathematical coupling between the two variables (acute and chronic), raised the possibility that the calculation is compromised and may result in spurious correlations. Indeed, in the first editorial, Lolli and colleagues (2017) demonstrated a moderate-to-large, positive correlation between the acute and chronic load (r = 0.5) for a simulated data set. It was concluded that any functions that are designed to quantify the association between acute and chronic load variables must be mathematically distinct from each other and not naturally associated if any true physiological explanations and/or likelihood of time-loss incidence are to be researched. Therefore, the simplest solution suggested is to not couple the acute:chronic phase in the same calculation. Taking for example days 0 to day -7 for the acute and then days -8 to day -35 for the chronic.

The second editorial from the group went further and used general linear models to assess the overall within-subject correlations English Premier League Football players calculated using the original acute:chronic workload ratio method of load quantification (Lolli et al., 2018). By regressing acute on chronic load, each participant was entered as a categorical factor. Results showed a large, inverse within-subject correlation between the acute:chronic workload ratio and its chronic denominator (r = -0.50). This meant that the use of the acute:chronic workload ratio biased a player's status of acute load as too low when prior chronic load was high, and vice versa. This reaffirmed the requirement for further research to establish optimal load quantification methods for practical utility in applied settings.

2.3.2.4 Exponentially Weighted Moving Average

Following the initial work by Menaspa (2017), Lolli and colleagues (2017) and Lolli and colleagues (2018), a proposed new method to load quantification, potentially mitigating the issues raised surrounding the decaying nature of fitness and fatigue overtime associated with the acute:chronic workload ratio approach, was introduced (Williams et al., 2017). The use of exponentially weighted moving averages (EWMA), which assigns a decreasing weighting for each older load value was suggested (Williams et al., 2017).

Specifically, the exponentially weighted moving average for any given day is calculated by:

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

where λ_a is a value between 0 and 1 that represents the degree of decay, with higher values discounting the older observations at a faster rate. The λ_a is given by:

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

where N is the chosen time decay constant, typically 7 days for the acute and 28 days for the chronic.

Subsequently, the EWMA is then calculated as:

$$EWMA = \frac{\text{acute } EWMA_{today}}{\text{chronic } EWMA_{today}}$$

This new approach to load quantification was then applied to the same three fictious athletes presented in the article by Menaspa (2017). Very different load ratios compared to the acute:chronic workload ratio were observed as shown in Figure 2.4 (Williams et al., 2017).

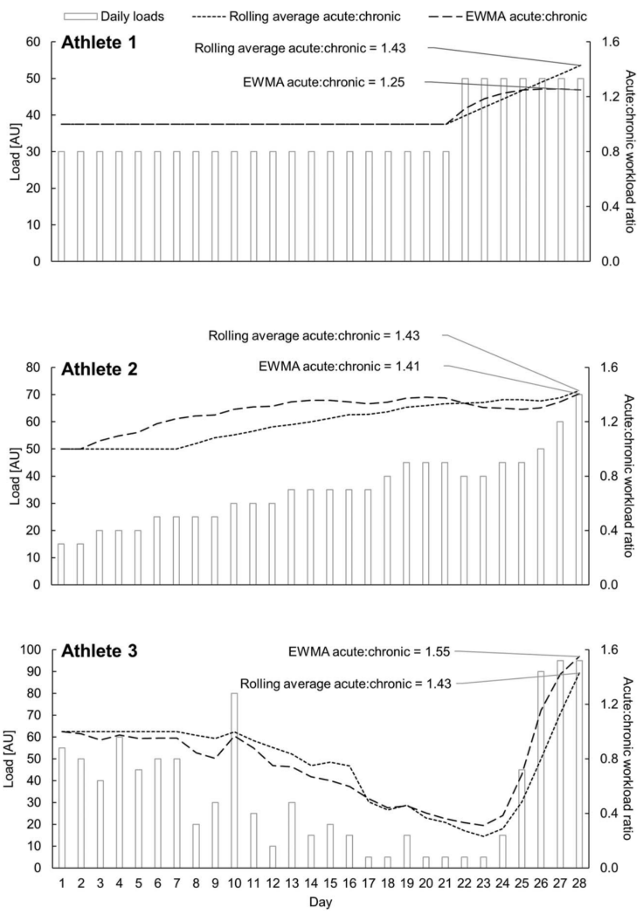


Figure 2.4. A worked example of the EWMA versus ACWR on fictious data from Menaspa (2017) (taken from Williams et al., 2017).

As presented in Figures 2.3 and 2.4, each athlete had an acute:chronic workload ratio of 1.43, whereas using the exponentially weighting moving average approach, loading values ranged from 1.25 (athlete 1) to 1.55 (athlete 3) suggesting very different likelihoods of injury incidence. Thus, the exponentially weighting moving average approach may be better suited to the modelling of load than the acute:chronic workload ratio rolling average approach, further discussed in section 2.3.3.5.

The load quantification methods adopted in the ten studies that explored the potential relationship between match and training load and time-loss incidence are demonstrated in Table 2.4. Of the ten studies, six studies utilised the absolute load method of quantification, three studies adopted both absolute and the acute:chronic workload ratio methods and one study applied both the acute:chronic workload ratio and the exponentially weighted moving average approaches (Table 2.4).

Table 2.4. A review of the load quantification methods used in the studies exploring match and training load and time-loss incidence in all sports.

Author and Year	Absolute	Acute:Chronic Workload Ratio	Exponentially Weighted Moving Average
Anderson et al. (2003)	sRPE load	--	--
Dennis et al. (2003)	Number of balls bowled	--	--
Gabbett and Domrow (2007)	sRPE load	--	--
Gabbett and Ullah (2012)	Distance and high-speed running distance	--	--
Rogalski et al. (2013)	sRPE load	--	--
Colby et al. (2014)	Distance and high-speed running distance	--	--
Hulin et al. (2014)	sRPE load and number of balls bowled	sRPE load and number of balls bowled	--
Carey et al. (2017)	sRPE load, distance and high-speed running distance	sRPE load, distance and high-speed running distance	--
Bowen et al. (2017)	Distance and high-speed running distance	Distance and high-speed running distance	--
Murray et al. (2017)	--	Distance and high-speed running distance	Distance and high-speed running distance

2.3.3 Load and Time-Loss Incidence

It is a foregone conclusion that all elite sports clubs strive for success; and in order to achieve that maximum performance is required. It is often thought that increasing training load, through longer duration, more intense, training sessions is the best method to achieve this. However, this increases the likelihood of time-loss incidence occurrence and subsequently decreases squad availability (Carling et al., 2015), which as previously discussed has a negative effect on team performance (Carling et al., 2015; Williams at al., 2015).

Therefore, research exploring the relationship between match and training load and time-loss incidence occurrence gained significant interest following the introduction of the measures to assess load (sRPE and GPS-derived variables) and methods to quantify load (absolute, acute:chronic workload ratio and exponentially weighted moving average). Table 2.5 presents the findings of the studies exploring the relationship between load and time-loss incidence, which will be discussed in the subsequent sections. First, the relationship between training load and time-loss incidence will be explored (sections 2.3.3.1 and 2.3.3.2), before moving on to discuss studies which also consider match load (section 2.3.3.3). Studies utilising the acute:chronic workload ratio approach to load quantification will be discussed in section 2.3.3.4 before moving onto the most recently proposed quantification method, the exponentially weighted moving average approach, in section 2.3.3.5.

Table 2.5. A review of the results from the studies exploring match and training load and time-loss incidence in all sports.

Author and Year	sRPE load	Distance	High-Speed Running Distance	Other
Anderson et al. (2003)	Weekly training load and weekly injuries (r = 0.675)	--	--	--
Dennis et al. (2003)	--	--	--	<2 d (RR = 2.4) or >5 d (RR = 1.8) rest vs. 3-3.99 d rest <123 deliveries (RR = 1.4) or >188 deliveries (RR = 1.4) vs. 123-188 deliveries
Gabbett and Domrow (2007)	Weekly training load and injury in pre-season (OR = 2.12), early-competition (OR = 2.85) and late competition (OR = 1.50) for each arbitrary unit ↑ in training load	--	--	--
Gabbett and Ullah (2012)	--	>9 m very high-speed running distance (RR = 2.7) vs. ≤9 m very high-speed running distance per session		--
Rogalski et al. (2013)	1-week load 1750-2250 AU (OR = 2.44) or >2250 AU (OR = 3.38) vs. 1-week load <1250 AU 2-week load >4000 AU (OR = 4.74) vs. 2-week load <2000 AU Week-to-week change >1250 AU (OR = 2.58) vs. ± <250 AU	--	--	--

Colby et al. (2014)	--	Pre-season: 3-week TD 73721 m – 86662 m (OR = 5.49) vs. 3-week TD <73721 m In-season: 2-week TD 39618 m – 45257 m (OR = 0.43) vs. 2-week TD <39618 m Week-to-week change TD 549 m – 6955 m (OR = 0.49) vs. <549 m	Pre-season: 3-week HSR 864 m – 1453 m (OR = 0.23) vs. 3-week HSR <864 m	--
Hulin et al. (2014)	ACWR >1.00 (RR = 2.2) or ACWR >2.00 (RR = 4.5) increased injury risk in subsequent week vs. ACWR 0.50 - 0.99	--	--	High acute load and ↑injury risk in current week (p<0.001) High chronic load and decrease injury risk in current (p = 0.002) and subsequent (p = 0.017) week ACWR >1.00 balls bowled (RR = 2.1) or ACWR >2.00 balls bowled (RR = 3.3) ↑injury risk in subsequent week vs. ACWR 0.50-0.99 balls bowled
Carey et al. (2017)	--	ACWR 6:14 days best explained the variation in injury likelihood (R^2 = 0.91)	--	--

Bowen et al. (2017)	--	4-week TD 112244 m – 143918 m (RR = 1.64) vs. all other ranges for overall injury risk ACWR >1.76 TD (RR = 4.98) increased contact injury risk compared to all other ranges	4-week HSR 3502 m – 5123 m (RR = 2.14) vs. all other HSR ranges for non-contact injury risk 1-week HSR 856 m – 1449 m (RR = 1.73) vs. all other HSR ranges for overall injury risk	--
Murray et al. (2017)	--	Pre-season: ACWR >2.00 TD (RR = 8.41) vs. ACWR 1.00 - 1.49 TD EWMA >2.00 TD (RR = 8.74) vs. EWMA 1.00 – 1.49 TD In-season: ACWR >2.00 TD (RR = 6.52) vs. ACWR 1.00 – 1.49 TD EWMA >2.00 TD (RR = 21.28) vs. EWMA 1.00 – 1.49 TD	In-season: ACWR >2.00 HSR (RR = 4.66) vs. ACWR 1.00 – 1.49 HSR	The R^2 values for each modelled variable was improved using the EWMA model versus the ACWR model in all 10 comparisons, with a statistically significant difference present in 70% of the models

Key. RR = relative risk; OR = odds ratio; ACWR = acute:chronic workload ratio; TD = total distance; HSR = high-speed running distance.

2.3.3.1 Early Work Exploring Training Load and Time-Loss Incidence

The initial work seeking to examine the impact of load on the incidence of illness and injury was completed by Anderson et al. (2003), who conducted a study monitoring the training patterns and loads of female collegiate basketball players over one season; alongside the incidence of illness and injury. Twelve athletes completed self-report questionnaires following every training session detailing their session RPE (Borg et al., 1987), session duration and any current illnesses or injuries suffered. sRPE load was then calculated from the given RPE and duration for each training session and then summed to provide a weekly sRPE load value. The squad weekly average for sRPE load was then analysed using a Pearson product moment correlation between injured and non-injured and unwell and healthy groups. Results demonstrated a moderately positive correlation between total weekly training load and weekly injuries ($r = 0.675$, $p<0.01$; Table 2.5). No correlation was found between total weekly training loads and illness ($r = 0.099$).

There are limitations with both the study design and the analysis undertaken by Anderson and colleagues (2003). With only a small n (12) of collegiate level athletes the overall power of the dataset is minimal, especially compared to subsequent studies (Table 2.3). Additionally, with the collegiate level of competition, confounding factors such as additional load accumulated through other sporting endeavours, which were subsequently not accounted for in the athlete's weekly load, could have affected the athlete's injury and illness risk. Moreover, the study design makes no reference to match load, which is typically the biggest load of a training week and is therefore likely to affect time-loss incidence risk and should be included in any weekly load calculation. The individual differences in accumulated load should also not be disregarded, thus, averaging the squad data is not optimal due to the differences in individual load. Therefore, it may have been more appropriate to carry out the analysis of individuals rather than averaging the loads, injuries and illnesses to squad level.

Following the requirement for a greater number of elite level participants the risk of injury in first class cricketers was examined (Dennis et al., 2003). External load measures of 90 male fast bowlers was observed for two seasons. The number of balls bowled during training sessions and matches was quantified by examining fixture scorecards and conducting surveillance during training sessions. Injury data was obtained through the Injury Surveillance System implemented by Cricket Australia and administered by medical professionals for each State and National squad. Only injuries that were reported as having a gradual bowling mechanism were included in the study. Therefore, injuries identified as having an acute onset or being collision-type injuries, such as slipping or colliding with another player, were not examined. Results showed that compared to the reference group of 3-3.99 days rest between bowling sessions, bowlers with an average of less than 2 days rest between session more than doubled their risk of a gradual onset bowling-related injury (risk ratio (RR) = 2.4). Similarly, 5 or more days between sessions almost doubled the risk (RR = 1.8) of such injuries. The practical implications of these findings make it hard to transfer into the applied setting. Test cricket, one of the three main formats, requires players to perform repeatedly for five consecutive days, therefore stating 3-3.99 days of complete rest between bowling sessions is impractical. Furthermore, the findings of the study go on to state, that compared to a reference group of 123 – 188 deliveries per week, bowlers with an average of fewer than 123 deliveries per week (RR = 1.4) or more than 188 deliveries per week (RR = 1.4) may also be at an increased risk of gradual onset bowling-related injuries. The results of both the days rest between bowling sessions and the number of deliveries per week suggest a U-shaped curve, where a middle ground of 'optimum load' may have practical utility. However, with the advancement of research in more recent years, the studies design flaws and limitations are more obvious and therefore the methodological approaches of studies exploring training / match load and injury and illness rates have advanced.

Following these initial research insights into the relationship between training and match load and injury and illness rates, there was a substantial expansion in the research output examining the load : injury / illness relationship, especially in Australia and in sports such as Rugby League and Australian Rules Football. One researcher in particular, Tim Gabbett, completed numerous studies from 2005 onwards developing load : injury relationship models and proposed guidelines by which applied practitioners could potentially decrease injury and illness rates within their respective sports.

2.3.3.2 Training Load and Injury Incidence

One of the early papers investigating the potential relationship between training load and injury aimed to develop predictive statistical models that would estimate the influence of training load on training injury in Rugby league players (Gabbett and Domrow, 2007). Training load and injury data were collated from 183 sub-elite Rugby league players from a single club over the course of two competitive seasons. Multiple fitness assessments were undertaken periodically throughout the season (off-season, pre-season, early-competition and late-competition), including anthropometry (stature, body mass, skinfolds), muscular impulse (vertical jump), speed (10 m, 20 m, 40 m), agility (L run) and estimated aerobic fitness (multi-stage fitness test). Each player participated in two to three field-training sessions per week, with the intensity of each training session estimated using the subjective, modified Borg CR-10 RPE scale, used to calculate sRPE load. Injury was defined as any pain or discomfort that prevented a player from completing the training session in which they were participating.

In terms of training load and injury incidence, overall incidence was 88.5 per 1000 training hours, with the chi-squared test demonstrating injury incidence was higher ($p = 0.001$) in the pre-season training phase (137.7 per 1000 h) than the early-competition (76.0 per 1000 h) and late-competition (62.6 per 1000 h) training phases. This matched the training load volumes, where the pre-season training load (weekly average 1891 AU) was greater than that of the early-competition (1345 AU) and late-competition (1488 AU) ($p = 0.003$). Therefore, when training load was increased, it was suggested that an increase in injury incidence occurred as a result. Logistic regression analysis of the influence of training load on individual physical fitness and likelihood of injury demonstrated how the log of training load per week affected injury incidence during the pre-season (odds ratio (OR) = 2.12), early-competition phase (OR = 2.85) and late-competition phase (OR = 1.50). In each case the odds ratio represents the increased likelihood of injury incidence for a one arbitrary unit increase in training load (Gabbett and Domrow, 2007).

The statistical models and findings of Gabbett and Domrow (2007), provided a basis from which multiple research avenues have been explored. However, this early work failed to register match load data, focusing only on training load data, therefore missing arguably for some sports, the biggest load of the week, as demonstrated in section 2.2. Furthermore, the training load data of the study presented here reported sRPE for field-sessions only, therefore also disregarding load accumulated from strength and conditioning sessions. In addition, no objective methods were used to assess training load.

The analysis of load using an objective measure was not examined in team sports, such as Rugby League and Australian Rules Football, until Gabbett and Ullah (2012) investigated the relationship between running loads and soft-tissue injury in elite team sport athletes. Training load data and the incidence of lower body soft-tissue injuries were collected from one club for a single National Rugby League season. A total of 117 skills training sessions were monitored during both the pre-season and in-season periods. Objective, GPS data providing information on speed and distance data was collected. Discrete movement velocity bands were used to differentiate the distances at which each player accumulated load; very low-speed (0-1 $m{\cdot}s^{-1}$), low-speed (1-3 $m{\cdot}s^{-1}$), moderate-speed (3-5 $m{\cdot}s^{-1}$), high-speed (5-7 $m{\cdot}s^{-1}$) and very high-speed (>7 $m{\cdot}s^{-1}$) velocities. Acceleration data and repeated high-intensity effort (RHIE) bouts were also recorded. A RHIE bout was defined as 3 or more high-acceleration, high-speed or contact efforts with <21 seconds recovery between efforts (Austin et al., 2011). An injury was defined as any non-contact, lower body soft-tissue injury (including muscular strains, tear and tendon injuries) suffered by a player during a training session, with all injuries diagnosed by the club physiotherapist and classified as transient (no training missed), time-loss (any injury resulting in missed training) or missed match (any injury resulting in a subsequent missed match). Injury incidence rates were then calculated by dividing the total number of injuries by the total number of training hours and expressed as rates per 1000 h. A frailty model, an extension of the Cox proportional regression model for recurrent events, was applied to calculate the relative risk of injury after adjusting for all training data.

Results showed that the incidence of transient soft-tissue injury was 37.4 per 1000 h, 42.1 per 1000 h for time-loss injuries and 13.1 per 1000 h for missed match injuries. The frailty model results demonstrated that the risk of transient injury was 2.7 times higher when very high-speed running distance exceeded 9 m per session, compared with ≤9 m per session. The authors stated that this finding highlights the relationship between the volume of high-speed running and injury risk in elite team sport athletes. However, only 9 m of sprinting per session is a negligible volume of load and therefore very difficult to translate into applied practice, especially given the weight of evidence to support the argument that high-speed running distance elicits a protective mechanism against soft-tissue (specifically hamstring) injury (Edouard et al., 2019). In essence, strengthening exercises and sprinting in isolation are not enough to minimise injury risk. For both tissue preparedness and performance, sprinting is an important training method. Therefore, it is important for future research to fully consider the impact of high-speed running distance on time-loss incidence risk. It appears that there may be a ‘balance’ to be struck, between high-speed running distance to enhance tissue preparedness and performance (Gabbett, 2015), yet not recommending too much to cause an injury (Edouard et al., 2019).

To conclude, the studies of Gabbett and Domrow (2007) and Gabbett and Ullah (2012) suggest that increased training load increases the risk of injury incidence. However, both studies made no to, or accounted for, match load; typically, the largest daily load in an elite sport performers training week and therefore crucial when assessing the load : injury relationship.

2.3.3.3 Match and Training Load and Injury Incidence

This gap in the research literature was addressed when absolute match and training load measures were taken, and its relationship with injury risk modelled, in elite Australian Rules Footballers (Rogalski et al., 2013). Forty-six athletes were monitored over one season of competition using the sRPE (internal, subjective) measure of load. Rolling weekly sum and week-to-week changes in load were modelled against injury incidence using logistic regression models. Odds ratios (OR) were reported against a reference group of the lowest training load range. As previously outlined the sRPE method of subjective load monitoring is calculated by multiplying the rating obtained using a modified Borg CR-10 RPE scale by the session duration (min) to produce a session load in arbitrary units (AU). All injuries were categorised by the club’s physiotherapist and defined as incidence resulting in a modified training programme, missed training session or missed match. The mechanism in which a player acquired an injury was also classified, as being either intrinsic (internal; overuse, overexertion) or extrinsic (external; collision, contact).

For each day a player was involved in a training session or match, their previous 1-, 2-, 3-, and 4-week individual loads were calculated. Relationships between training and match loads and injury were investigated in two ways. Firstly, whether accumulated loads were associated with injury incidence by assessing the link between 1, 2, 3 and 4 weekly cumulative loads and subsequent injury incidence and secondly, by analysing the week-to-week changes in load (e.g. whether a large increment between weekly loads was associated with injury). Load exposure values and injury data (injury vs. no injury) were then modelled in a logistic regression analysis. Overall injury incidence was compared per 1000 h for both training and match exposure between pre-season and in-season phases using Chi square analysis.

Overall injury incidence increased from pre-season to in-season (21.9 per 1000 h vs. 32.8 per 1000 h, p = 0.002), despite average individual weekly loads being greater in pre-season compared to in-season (2027 AU vs. 1651 AU, p<0.001; Table 2.5). Interestingly, extrinsic injuries and intrinsic injury incidences were not different during the in-season phase (18.9 per 1000 h vs. 13.9 per 1000 h). Players who exerted one-weekly loads in-season between 1750 AU and 2250 AU and >2250 AU were at significantly higher risk of injury compared to the reference group of <1250 AU (OR = 2.44, p=0.007 and OR = 3.38, p=0.001, respectively; Table 2.5). Two week in-season loads of >4000 AU (compared to a reference group of <2000 AU) were associated with a four-fold increase in occurrence of injury (OR = 4.74, p=0.033). A similar outcome was seen when comparing the absolute change in load (from one week to the next), a week-to-week change of >1250 AU (compared to a reference group of ± <250 AU) elicited a 2.5 times greater increase in injury incidence (OR = 2.58, p=0.002). This was the first study to highlight the importance of monitoring both the absolute and week-to-week changes in match and training load for injury risk. However, only subjective load data was collected in this study, and it may be that objective load data may provide an extra insight into the load : injury relationship.

In a similar study design, one year after the publication of the work by Rogalski and colleagues (2013), a study in Australian Rules Footballers assessing the relationship between objective loads (derived GPS units) and injury risk, over one season of competition (Colby et al., 2014). Accelerometer and GPS-derived running load data was collected from 46 players from a single

AFL club and all injury information was classified by the club's physiotherapist, with the season split by pre-season and in-season phases. The mechanism in which a player acquired an injury was also classified, as being either intrinsic (internal; overuse, overexertion) or extrinsic (external; collision, contact) in nature, with only intrinsic injuries being considered with respect to injury risk for this particular study.

The GPS-derived running load data analysed in relation to intrinsic injury risk included, but was not limited to, total distance (total distance covered walking, jogging, fast running and sprinting) and high-speed running distance (total distance covered above 75% of the individual players maximum speed, as determined from pre-season 20 m sprint testing or GPS game data). Multiple regression models were used to compare the cumulative (1-, 2-, 3-, and 4-week loads) and absolute change (week-to-week changes) in loads between injured and uninjured players for all GPS-derived variables. For each variable, the data cases were split into three even groups, with the first (low load) group used as the reference group for the analysis. Odds ratios (OR) were calculated to determine the injury risk at a given cumulative load or absolute change in load. The rationale behind solely analysing the relationship between load and intrinsic injury risk was that these are more directly related to soft-tissue injuries especially from a training load perspective (Gabbett et al., 2010).

Results (as demonstrated in Table 2.5) of the regression models during the pre-season phase showed that 3-week total distance of between 73721 m and 86662 m (mid-range group) (compared to the reference group <73721 m) increased the odds of non-contact injury risk by five times (OR = 5.49, p = 0.008). However, no relationship was observed when 3-week total distance was greater than 86662 m (p = 0.922). When assessing 3-week high-speed running distance, load of between 864 m and 1453 m (mid-range group) (compared to the reference group <864 m) resulted in a decreased risk of non-contact injury (OR = 0.23, p = 0.045). No relationships were observed between the absolute week-to-week changes in distance and high-speed running distance and non-contact injury risk.

Results of the regression models during the in-season phase showed that 2-week total distance of between 39618 m and 45257 m (mid-range group) (compared to the reference group <39618 m) decreased the risk of non-contact injury (OR = 0.43, p = 0.024), with no relationship observed at the high range (>45257 m, p = 0.059). When assessing injury risk and absolute week-to-week change in load, a week-to-week change of between 549 m and 6955 m resulted in an decreased intrinsic injury risk (OR = 0.49, p – 0.043), with no relationship observed at the high range (>6955 m, p = 0.081). There were no relationships between high-speed running distance and non-contact injury risk for any of the cumulative load or absolute change variables. The results suggest that, during the pre-season phase mid-range 3-week total distance and high range 3-week high-speed running distance placed the players at the highest risk of non-contact injury. With only a single season of data collection, the volume of data at the higher ranges would be lacking and therefore a limitation of this study. These findings do however suggest a protective effect of a moderate load of high-speed running, similar to that of Gabbett and Ullah (2012) and Edouard and colleagues (2019), as previously discussed. Tables 2.3 and 2.4 demonstrate how exclusively up until the mid-2010's match and training load was quantified exclusively using the absolute load method of quantification. However, with this potential protective mechanism at mid-range load values, a model exploring the relationship between short- and long-term effects of load accumulation was created.

2.3.3.4 Acute:Chronic Workload Ratio

In 2016, the study of the load : injury relationship in sporting populations changed dramatically. As previously mentioned, the quantification of load transformed from just observing the absolute load in isolation, to a ratio approach, by assessing the short- (acute) and long- (chronic) term effects of load accumulation on time-loss incidence. By aggregating findings of three independent research studies, the acute:chronic workload ratio (ACWR) was created (see section 2.3.2.3 for definition and calculation of acute:chronic workload ratio).

One of the original articles used to create a proposed guide on how the acute and chronic loads of athletes could be manipulated to minimise the risk of injury (Figure 2.5), was published in 2014 by Hulin and colleagues. The objectives of the study were to determine if the comparison of acute and chronic load was associated with an increased injury risk in elite cricket fast bowlers. Data were collected from 28 fast bowlers who completed a total of 43 individual seasons over a 6-year period. One-week data (acute load) and 4-week rolling average data (chronic load) were calculated for both the number of balls bowled (objective) and the sRPE load (subjective), with the size of the ratio between the acute:chronic phases providing either a positive or negative training stress balance (TSB), which was expressed as a percentage. For clarity, TSB is an alternative name for the acute:chronic workload ratio, whereby an acute:chronic workload ratio of 0.5 would equate to a TSB of 50%. The difference between acute and chronic phases provides either a positive TSB where the chronic load is greater than the acute load so <1.0 (ACWR) or <100% (TSB) or a negative TSB where the acute load is greater than the chronic load so >1.0 (ACWR) or >100% (TSB). The likelihood of sustaining an injury was analysed using a logistic regression model, with injury as the dependent variable and training stress balance for both internal and external load variables as the independent, predictor variables. All injury data was collated by the club's medical staff, with only time-loss non-contact injuries included in the analyses.

The main findings (as demonstrated in Table 2.5) suggest a 'U-shaped' relationship between the acute:chronic workload ratio and the likelihood of subsequent injury. The relationship between internal sRPE load and non-contact injury risk demonstrated an increased risk of injury in the subsequent week if the acute:chronic workload ratio exceeded 1.0, with a significantly (four times greater) increased non-contact injury risk when acute:chronic workload ratio exceeded 2.00 (ACWR >1.00: RR = 2.2, p<0.001; ACWR >2.00: RR = 4.5, p = 0.009 vs. ACWR 0.50-0.99). Fifty-seven per cent of all injuries occurred within one week of a high acute:chronic workload ratio (i.e. >1.0). Furthermore, high acute external load (balls bowled) was associated with an increased non-contact injury risk in the current week. When comparing the acute:chronic phases and external load (balls bowled), a high acute:chronic workload ratio (>1.0) was associated with a two-times greater risk of non-contact injury (RR = 2.1, p = 0.010) in the subsequent week. Furthermore, bowlers with an acute external load of more than 200% of their chronic load (i.e. ACWR >2.0) had three-times greater risk of non-contact injury (RR = 3.3, p = 0.033) compared to players with an acute:chronic workload ratio of between 0.50 and 0.99. Sixty-three per cent of all injuries occurred within one week of a high acute:chronic workload ratio value >1.0. However, a protective mechanism was seen when a player exhibited a high chronic load, with a decreased injury risk in the current (p = 0.002) and subsequent (p = 0.017) week demonstrated.

This was the first study to examine the potential relationship between acute and chronic workloads and injury risk in elite cricket fast bowlers, and it adapted the performance model proposed by Bannister and colleagues (1991) by calculating the difference between acute and chronic load exposures. While Bannister and colleagues (1991) stated that preparedness for competition grows as the chronic load outweighs the acute load, the findings of the study by Hulin and colleagues (2014) suggests that injury risk also increases in the following week.

As previously mentioned, the methods by which load was quantified by Hulin et al. (2014) was novel at the time, and along with two other papers by the same research group it led to the production of figure 2.5; demonstrating the 'U-shaped' relationship between the acute:chronic workload ratio and the likelihood of subsequent injury.

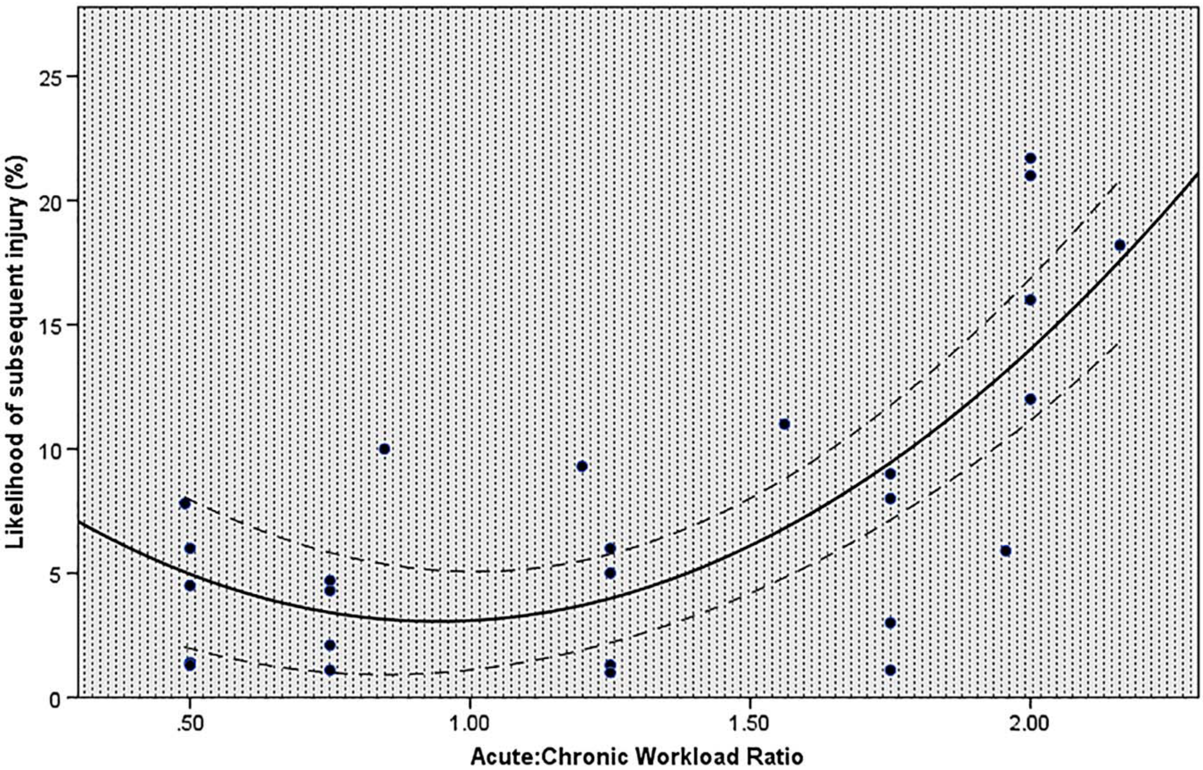


Figure 2.5. The acute:chronic workload ratio and subsequent injury likelihood from studies of three different sports (taken from Blanch and Gabbett, 2016).

Following the introduction of the acute:chronic workload ratio, researchers then looked to explore the relationship between load, quantified using the acute:chronic workload ratio, and its influence on match injury risk. Specifically, Carey and colleagues (2017) examined which combination of acute and chronic time windows best explained injury likelihood. Load and injury data were collected from 53 Australian Rules footballers over 2 seasons of professional competition. Acute:chronic workload ratios were calculated for each player daily and modelled against non-contact match injury. Objective (GPS) and subjective (sRPE) load data was collected from all training sessions and matches and then quantified using the acute:chronic workload ratio with 56 possible combinations of acute and chronic time windows (acute phases of 2, 3, 4, 5, 6, 7, 8, 9 days and chronic phases of 14, 18, 21, 24, 28, 32, 35 days were considered). The GPS variables used in this study included distance (m) (all distance covered above 0.8 $m{\cdot}s^{-1}$), high-speed running distance (m) (all distance covered above 6.7 $m{\cdot}s^{-1}$) and moderate-speed running distance (MSR) (m) (all distance covered between 5.0-6.7 $m{\cdot}s^{-1}$).

Injury lag periods were also considered to account for the possible delayed effects on injury occurrence; therefore three lag periods were considered: (1) on that day (no lag time), (2) on that day or the following 2 days or (3) on that day or the following 5 days. Carey and colleagues (2017) suggested that these periods were chosen because they represented the risk in: (1) a single session, (2) a short period post-session not including the next main session, and (3) a longer period incorporating the next main session but not overlapping with more than one competitive match. Injuries were recorded and classified by the club's medical staff using the Orchard Sports Injury Classification System (OSICS; Ray and Orchard (2007)) and defined as those causing a player to be unavailable for training or competition. The study focused on time-loss non-contact injuries in matches only, stating the reasons for this as that matches were associated with high injury likelihoods per exposure time.

All acute:chronic workload ratios were modelled against injury likelihood using quadratic regression, therefore load variables were split into four bins (ACWR of 0.5, 1.0, 1.5, 2.0) for the analysis. The ability of each acute:chronic workload ratio to explain injury likelihood was assessed using the R^2 statistic. Results demonstrated that the ratio 6:14 days distance load best explained the variation in injury likelihood in training sessions and matches combined (mean R^2 = 0.91). However, when the relationship was decomposed by session type, considerably different injury risk profiles were observed with matches being associated with higher injury likelihood than training sessions, irrespective of the players acute:chronic workload ratio (RR = 4.0).

When summarising the quadratic regressions analysis, with only match injury included, moderate speed running distance with a 3:21 day ratio consistently explained the injury likelihood for each injury lag period (mean R^2 = 0.76-0.82). The similarity in model performance across each injury lag period suggested that the daily acute:chronic workload ratio can inform injury risk assessment in Australian Rules Football matches and that including a forward-looking lag period does not significantly improve the ability to explain variations in match injury rates. Injury models using previously reported parameters of 7:28 time windows explained less of the variance (mean R^2 = 0.04-0.41) in this particular study population. However, the authors did state that the acute:chronic time windows can be sport specific with differences in days between matches and training schedules both important factors to consider alongside the differences in physical demands of other sports. From the results of this study, it was concluded that Australian Rules Footballers load is best monitored using a 3:21 moderate speed running distance acute:chronic workload ratio because of its association with non-contact match injury likelihood.

It could be argued that the study's findings are limited because injury likelihood models only included non-contact match injuries, despite the fact that it was reported that more than half of all injuries that occurred over the course of the two seasons were in training (100 training injuries out of 159 total match and training injuries, i.e. 63%). Furthermore, it is important to note that the authors grouped load data from training and matches yet considered the effect only on non-contact match injuries. To provide a more holistic overview of time-loss incidence occurrence, at an initial level of analysis, load and injuries from both training and matches should be analysed together. From the findings of this study by Carey and colleagues (2017), a relationship between the acute:chronic workload ratio and injury likelihood was demonstrated, however, with concerns surrounding the injury inclusion criteria in the data analysis and the time-windows being specific to Australian Rules footballers, further research was required to clarify the potential load : injury relationships.

Following the requirement for load : injury relationship studies to assess overall injury incidence (to include injuries from both training and matches), Bowen and colleagues (2017) investigated the relationship between physical load and injury risk in elite youth football players. Load and injury data were collected from 32 elite youth football players from one English Premier League category 1 academy over two seasons of competition, comprising 52 individual player seasons. Objective GPS data was collected from all on-pitch training sessions and matches with the following GPS variables examined: total distance (this includes all walking, jogging, fast running and sprinting), high-speed running distance (total distance covered >5.6 $m{\cdot}s^{-1}$) and accelerations (defined as a change in GPS speed data for 0.5 s with a maximum acceleration in the period of at least 0.5 $m{\cdot}s^{2}$). Injury information was classified and collated by the club's medical staff and a recordable injury was defined as one that caused any absence from future training session or match.

Data was quantified using two methods: cumulative weekly sums and the acute:chronic workload ratio. On any given day, the previous 1-week, 2-week, 3-week and 4-week loads were calculated and then classified into discrete ranges (low, moderate-low, moderate-high, high, very high) using z-scores (mean and standard deviations) and it was the relationships between these weekly cumulative loads and subsequent injury that were investigated. Secondly the 7:28 day acute:chronic workload ratio was split into discrete z-score ranges based on the chronic proportion of the ratio (categorised by median score). A binary logistic regression model was used to compare the load variables between injured and non-injured players for all quantification methods. Cumulative load and acute:chronic workload ratio were independently modelled as predictor variables and relative risk was calculated to determine the injury risk above and below given workloads or ratios, with injuries also analysed as total overall incidence and contact / non-contact separately.

The overall incidence of injury in competition was over four times that of training (33.5 per 1000 h match exposure vs. 7.9 per 1000 h training exposure). In particular the incidence of contact injuries in matches were considerably greater than in training (24.2 per 1000 h vs. 2.3 per 1000 h). The results of the binary logistic regression on the absolute accumulated load variables demonstrated that performing high total distance over a 4-week cumulative period was associated with the greatest significant overall injury risk compared to all other total distance ranges (RR = 1.6, $p = 0.031$; Table 2.5). A low 1-week total distance (0 m – 8812 m) reduced the risk of overall injury risk and non-contact injury risk (RR = 0.25, $p = 0.018$ and RR = 0.30, $p = 0.001$, respectively). Moderate-high 4-week high-speed running distance more than doubled non-contact injury risk when compared to other ranges (RR = 2.14, p = 0.003; Table 2.5), with moderate-high 1-week high-speed running distance related to overall injury risk (RR = 1.73, p = 0.029; Table 2.5).

From the acute:chronic workload ratio variables, the risk of contact injury increased almost five-fold when the ACWR total distance exceeded 1.76 (very high z-score range) compared to all other ranges (RR = 4.98, p = 0.019). When players had a low chronic high-speed running volume (<938 m), in conjunction with a high acute:chronic workload ratio (1.41-1.96) non-contact injury risk was more than doubled (RR = 2.55, p = 0.022). Interestingly, having a high chronic high-speed running distance exposure (>938 m) and moderate-high acute:chronic workload ratio (0.91-1.34) also resulted in increased non-contact injury risk (RR = 2.09, p = 0.033). Unsurprisingly, players with a low acute:chronic workload ratio (0.0-0.36) for any chronic high-speed running distance exposure, significantly reduced the overall injury risk was returned (RR = 0.47, p = 0.022).

This was the first study to examine the relationship between accumulated GPS-derived load data and acute:chronic workload ratio with contact and non-contact injury incidence in Football. In line with other studies mentioned above, many of the GPS variables presented in this paper (total distance and high-speed running distance) were found to be related to injury risk; with some findings even suggesting as great as a five-fold increases in risk (for contact injury when ACWR >1.76 for distance). However, by neglecting to collect a subjective measure of load, sRPE for example, the relationships between internal load and time-loss incidence still remains largely unanswered. Nonetheless, the findings presented in the study provide empirical support for the monitoring of training loads in elite sports environments and agree with those of Colby and colleagues (2014), who also demonstrated that various 3-week cumulative loads had the strongest association with injury risk (in Australian Rules Footballers during both the pre- and in-season phases).

As can be seen from the papers presented in sections 2.3.3.1 – 2.3.3.4, the load : injury relationship research has gained significant traction since the early 2000's. The ability to identify trends and relationships between both objective and subjective measures of load and injury incidence has been deemed to be of great practical utility in the applied field setting.

However, with growing evidence and support for the acute:chronic workload ratio approach to load monitoring, other researchers flagged concerns surrounding the mathematical calculations by which the ratio was calculated and the mathematical coupling / large inverse within-subject correlations between the acute:chronic elements of the ratio, (as presented in section 2.3.2.3; Lolli et al., 2017; Lolli et al., 2018).

2.3.3.5 Exponentially Weighted Moving Average

With a growing body of evidence supporting the acute:chronic workload ratio as a method of load quantification, there appears to be merit in considering both the acute and chronic aspects of load when exploring the likelihood of time-loss incidence occurrence. However, with the issues surrounding the acute:chronic workload ratio, researchers sought to address some of these issues whilst maintaining consideration of both the acute and chronic aspects of load. This led to the creation of the exponentially weighted moving average approach (see section 2.3.2.4 for definition and calculations).

The differences between the acute:chronic workload ratio and the exponentially weighted moving average models for predicting subsequent injury risk were examined in 59 elite Australian Rules footballers across two seasons of competition (Murray et al., 2017). Objective GPS technology was used to quantify the external load of players and all non-contact time-loss injuries were recorded. A total of 92 individual player seasons were assessed, where 33 (56%) of the players completed both seasons and 26 (44%) completed one of the two seasons. Each season comprised a 16-week pre-season period and a 23-week in-season period, with GPS load calculated throughout both phases for all training sessions and matches. The load variables collected from the GPS units were total distance (m), low-speed running distance (<1.7 $m{\cdot}s^{-1}$), moderate-speed running distance (1.7-5.0 $m{\cdot}s^{-1}$), high-speed running distance (5.0-6.7 $m{\cdot}s^{-1}$) and very high-speed running distance (>6.7 $m{\cdot}s^{-1}$). An injury was defined as any non-contact time-loss injury sustained during either training or competition that resulted in a missed training session or match. Injury likelihoods were calculated based on total number of injuries relative to the total exposure, with relative risk then calculated. Rolling average acute:chronic workload ratio and the exponentially weighted moving average methods of load quantification were then calculated from the GPS data and divided into the following ranges: (1) very low ≤0.49, (2) low 0.50-0.99, (3) moderate 1.00-1.49, (4) high 1.50-1.99 and (5) very high ≥2.00.

The likelihood of sustaining a non-contact injury was analysed using two binary logistic regression models. The acute:chronic workload ratio and the exponentially weighted moving average were independently modelled as the predictor variable and injury/no injury as the dependent variable. The very high load range (ACWR or EWMA ≥2.00) was used as the reference group to which all other ranges were compared. Differences between the two quantification methods were determined using a one-way analysis of variance (ANOVA), with the R^2 value for each model analysed to compare differences between the quantification methods.

A total of 40 non-contact injuries were sustained over the two-season period, 18 during pre-season and 22 during the in-season phases. The hamstring (53%) was the most commonly injured site, followed by thigh (18%) and calf (also 18%). The exponentially weighted moving average and acute:chronic workload ratio produced different values and were poorly related to each other (R^2 = 0.43, p = 0.001). Typically, the exponentially weighted moving average method returned lower values than the acute:chronic workload ratio model for the same daily observations for moderate, high and very high ranges (moderate: 1.07 ± 0.22 vs. 1.19 ± 0.12, p = 0.021; high: 1.27 ± 0.21 vs. 1.64 ± 0.12, p = 0.012; very high: 1.51 ± 0.22 vs. 2.29 ± 0.20, p = 0.001, respectively). No difference was observed between the very low and low ranges (p>0.05).

In terms of injury likelihoods for the two different quantification models, during the pre-season phase, an acute:chronic workload ratio of >2.00 for total distance was associated with an 8-fold increase in risk of non-contact injury compared to those with an acute:chronic workload ratio of 1.00-1.49 (Table 2.5). No other relationships were observed for any of the acute:chronic workload ratio variables and injury likelihood during the pre-season phase. However, using the exponentially weighted moving average model, numerous relationships were detected; when the exponentially weighted moving average range was >2.00, compared to 1.00-1.49 (total distance RR = 8.74, p = 0.002; moderate-speed running distance RR = 6.03, p = 0.028, respectively; Table 2.5). A similar pattern was also seen during the in-season phase, with an acute:chronic workload ratio of >2.00 for both total distance and high-speed running distance associated with an increased likelihood of non-contact injury (Table 2.5). When using the exponentially weighted moving average model, players who exceeded 2.00 for total distance, experienced up to 21-fold increases in non-contact injury risk (Table 2.5). When assessing the variance (R^2) in injury between models (ACWR vs. EWMA), notable differences are seen between the two quantification methods as shown in Table 2.6.

Table 2.6. Variance (R^2) in injury explained by the acute:chronic workload ratio and exponentially weighted moving average models. Re-drawn table from Murray et al. (2017).

Workload Variable	ACWR Quantification Method		EWMA Quantification Method	
	Pre-Season	In-Season	Pre-Season	In-Season
Total Distance (m)	0.21	0.40	0.87*	0.78*
Low-Speed Distance (m)	0.47	0.43	0.79*	0.75*
Moderate-Speed Distance (m)	0.32	0.47	0.82*	0.77*
High-Speed Distance (m)	0.13	0.37	0.77*	0.67
Very High-Speed Distance (m)	0.23	0.21	0.69	0.66

*denotes significant difference ($p<0.05$) from the acute:chronic workload ratio model.

Table 2.6 demonstrates the variance in injury likelihood that is explained by the variable and quantification method in question. During the pre-season phase for example, the regression analysis suggested that 21% (R^2 = 0.21) of the variance in injury likelihood was explained by using the total distance acute:chronic workload ratio as an explanatory factor. However, for the same variable (total distance), when applying the exponentially weighted moving average approach, a significantly greater amount of the variance in injury incidence (R^2 = 0.87) was explained (p = 0.042). The R^2 values for each modelled variable was improved using the exponentially weighted moving average model versus the acute:chronic workload ratio model in all 10 comparisons, with a statistical difference present in 70% of the models (denoted by the * in Table 2.6).

The work of Murray and colleagues (2017) was the first study to directly compare the two load quantification methods (ACWR vs. EWMA) on real world data; and this is still the only study to date to consider the relationship between the exponentially weighted moving average and injury incidence. These findings could provide sport science and medical staff at sports clubs with a more effective method of load management (i.e. the EWMA) when designing training protocols with cohorts playing Australian Rules Football. However, the inclusion of only non-contact injuries, along with the use of only objective GPS derived load information, are both limitations of the study. Assessment of internal measures of subjective load (e.g. sRPE load) could have strengthened the study and the consideration of all injuries (contact and non-contact) would have increased the size of the dataset and potentially added to the study's findings and applicability. As previously mentioned however, the findings of this study recommend the use of the exponentially weighted moving average model rather than the more commonly used acute:chronic workload ratio method.

2.3.3.6 Summary of Load and Time-Loss Incidence

Since the early 2000s the number of research articles exploring the relationship between load and injury/illness has increased exponentially. From the first research studies exploring the absolute load measures of subjective sRPE load to the more sophisticated objective measures (GPS-derived) quantified using the acute:chronic workload ratio and the exponentially weighted moving average, the landscape of load : injury relationship research has certainly developed over the years. The papers discussed in this section of the literature review demonstrate the path on which field has taken, with numerous new methods and practical applications for researchers and practitioners alike.

The sport of Rugby Union, an intermittent team sport where shorts periods of maximal or high-speed running exercise with collisions / contacts between players are punctuated by lower intensity exercise or rest (Nicholas, 1997), has not been well researched with regards to the load : injury relationship. Rugby Union has one of the highest reported match injury incidence rates among all professional team sports, with some studies reporting up to 218 injuries per 1000 player match hours (Brooks and Kemp, 2008), compared to football where injury rates of 27.5 per 1000 player match hours across 23 top European clubs was reported (Ekstrand et al., 2009).

Therefore, the potential relationship between load and time-loss incidence in elite Rugby Union players may assist practitioners seeking to address this high injury incidence rate. As demonstrated in the subsequent section of this review (section 2.4), this particular area of research has not been well explored in a sport where there is a clear requirement for the development of load management protocols.

2.4 Load and Time-Loss Incidence in Rugby Union

As previously stated, Rugby Union has significance on both the national and international stage, therefore improving squad availability at a domestic level of competition, will not only have a positive impact on the success of the sport nationally (Williams et al., 2015), but also the game as a whole by attracting greater crowds and subsequently greater financial rewards for the governing body (Chadwick et al., 2010). Research exploring match and training load and time-loss incidence in a variety of team sports (Basketball, Cricket, Rugby League, Australian Rules Football and Football) was reviewed in section 2.3. However, the effect of match and training on time-loss incidence in Rugby Union, a sport renowned for a high time-loss incidence rate (Brooks and Kemp, 2008). To date, five studies have been conducted examining injuries in elite Rugby Union, with only one study to date exploring the effect of match and training load on injury incidence (Tables 2.7 and 2.8).

Table 2.7. A review of the study design characteristics of the training load and injury in Rugby Union.

Study Details				Methodology		
Author and Year	**Sport**	**Level of Competition**	**Participants**	**Load Variables**	**Load Quantification**	**Injury / Illness Reporting**
Bathgate et al. (2002)	Rugby Union	Elite	Male; n = NA	--	--	Medical staff Match injuries only
Brooks et al. (2005a)	Rugby Union	Elite	Male; n = 546	--	--	Club's medical staff Match injuries only
Brooks et al. (2005b)	Rugby Union	Elite	Male; n = 502	--	--	Club's medical staff Training injuries only
Fuller et al. (2007)	Rugby Union	Elite	Male; n = 645	--	--	Club's medical staff Match contact injuries only
Cross et al. (2016)	Rugby Union	Elite	Male; n = 173	sRPE load (internal, subjective)	Absolute and ACWR sRPE load	Club's medical staff All injuries

Key. ACWR = acute:chronic workload ratio.

Table 2.8. A review of the results of the studies exploring training load and injury incidence in Rugby Union.

Author and Year	Incidence	Severity	Load and Injury Incidence	Other
Bathgate et al. (2002)	Match injury: 69.0 per 1000 h	Minor severity (≤7 d): 64% Major severity (≥8 d): 36%	--	Most common site: Head / face Contact injury: 43% Non-contact injury: 57%
Brooks et al. (2005a) (match)	Match injury: 91.0 per 1000 h	Average severity: 18 d Minor severity (≤7 d): 54% Major severity (≥8 d): 46%	--	Most common site: Anterior thigh Contact injury: 72% Non-contact injury: 28%
Brooks et al. (2005b) (training)	Training injury: 2.0 per 1000 h	Average severity: 24 d Minor severity (≤7 d): 37% Major severity (≥8 d): 63%	--	Most common site: Posterior thigh Contact injury: 43% Non-contact injury: 57%
Fuller et al. (2007)	--	Greatest loss of time: tackles (701.6 d per 1000 h)	--	Most common event: tackles (221 events per match) Highest risk per event: scrums (213.2 d per 1000 events) and collisions (199.8 d per 1000 events)
Cross et al. (2016)	Match injury: 101.7 per 1000 h Training injury: 3.3 per 1000 h	--	1-week sRPE load >1245 AU (OR = 1.68) vs. average week for injury risk in subsequent week Week-to-week change >1069 AU (OR = 1.58) vs. no change for injury risk in subsequent week 4-week sRPE load >8651 AU (OR = 1.39) vs. 4-week sRPE load <3684 AU for injury risk in subsequent week	--

Key. OR = odds ratio.

2.4.1 Injury Incidence in Rugby Union

The first study assess injury incidence in elite Rugby Union was undertaken in International players between 1994 to 2000 (Bathgate et al., 2002). Therefore, crossing the boundary, in 1995, to the start of the professional era. Prospective data were recorded of all match injuries sustained by the Australian International Rugby Union team by the team doctor and defined as one that forced a player to either leave the field or miss a subsequent match. The exact number of players involved in the study was not stated. A total of 143 match injuries were reported from 91 matches at an injury incidence of 69.0 per 1000 match exposure hours (Table 2.8). The match injury incidence was higher post the start of the professional era (1995 – present) compared to that of pre-professionalism (pre-1995) (74.0 per 1000 h vs. 47.0 per 1000 h). The most common site of match injury, with over a quarter of all incidence, was the head/face (25.1%). However, almost two thirds (64%) of all match injuries resulted in ≤7 days missed (minor severity). Despite a clear increase in match injury incidence over recent years (from 2002 – 2015), no explanation for the increase was suggested; for example, no measure of load and its impact on injury incidence was reported. Rather, the study reported descriptive findings regarding the incidence and severity of injury. A similar study was undertaken as a two-part large-scale epidemiological study of match injuries (part 1) and training injuries (part 2) in English professional players (Brooks et al., 2005a; Brooks et al., 2005b).

The study in English professional players was a two-season prospective design of their incidence, nature, severity and cause of match and training injuries (Brooks et al., 2005a; Brooks et al., 2005b). The first part, match injuries, investigated 546 players from 12 English Premiership clubs, with each respective team's medical staff reporting match injuries and exposure time for each individual player. An overall incidence of 91.0 per 1000 h of match exposure was reported, therefore higher than the 74.0 per 1000 h of match exposure conveyed in the study of International players in the professional era of Bathgate and colleagues (2002). An average severity of 18 d per match injury was stated, with minor (≤7 d) severity (54%) injuries accounting for just over half of all match injuries (major severity (≥8 d): 46%). Thus, major severity injuries accounted for ~10% greater proportion of match injuries compared to the data in International players (Bathgate et al., 2002). Contact injuries accounted for 72% of all match injury incidence which was coupled with anterior thigh as the most common site; specifically, the most common injury was a thigh haematoma. However, the authors suggested that their low severity meant these injuries (thigh haematoma), did not generally cause players to miss any subsequent matches. Hamstring injuries were the second most common site of match injury and the incidence of hamstring injuries was higher in backs compared to forwards. The authors suggested that the greater amount high-speed running completed by backs, compared to forwards (Lindsay et al., 2015; section 2.2) may contribute to this.

The second part of the study explored training injuries (Brooks et al., 2005b). In a similar study design, 502 players from 11 English Premiership clubs were monitored. Again, club's medical staff provided data on exposure time (this time to training) and training injuries for each individual player. Overall, training injury incidence was 2.0 per 1000 h of training exposure and average severity was 24 d. Twenty two percent of all training occurred in pre-season, yet pre-season accounted for 34% of all training injuries. Therefore, suggesting that the requirement for a solid chronic foundation of load exposure is potentially paramount in the prevention of the increased time-loss incidence typically seen during a pre-season phase (as suggested in section 2.3: Bowen et al., 2017; Murray et al., 2017). The anterior thigh was the most common site of training injury for both forwards and backs and given the focus of the preparatory pre-season phase and the running demand emphasis of physiological preparation for matches within training, this is unsurprising (Gabbett et al., 2010). At this stage in the history of research exploring injury incidence in Rugby Union, it was clear that match injury incidence was higher than that reported in training (91.0 per 1000 h vs. 2.0 per 1000 h; Brooks et al., 2005a; Brooks et al., 2005b). Furthermore, the contact nature of the injuries reported in matches (72%) prompted the exploration of the contact actions of Rugby Union and their propensity to cause injury (Fuller et al., 2007b).

2.4.2 Contact Actions and their Propensity to Match Injury

Rugby Union, a sport recognised for its contact / collision nature, subsequently means its risk of injury during matches is high (Brooks et al., 2005a). The majority of injuries at elite levels of competition result from the contact actions of the match play, and despite studies reporting the incidences and their apparent association with the contact elements of the sport, no information was present on the effect of the number and frequency of these contact actions on injury incidence (Fuller et al., 2007b). The relevance of this information was demonstrated in Football (Soccer), where the outcome of various tackle actions in men's International football was analysed (Fuller et al., 2004). The findings suggested that a high percentage of match injuries occurred during the tackle action. This was caused by a high frequency of tackles during a Football match rather than a high incidence of injury per tackle event, which was actually relatively low. This consequently led to the broadened definition of what constituted serious foul play within the Laws of Football, and alterations to the sanctions for such offences. Therefore, the requirement for the quantification of the number contact actions' and their propensity to cause injury in Rugby Union is justified.

A study to determine the incidence of contact events in professional Rugby Union matches, and their tendency to cause injury was undertaken by Fuller et al. (2007b). A two-season study of 645 players from 13 English Premiership clubs was carried out, with the incidence of contact events, injury incidence and risk (days lost per 1000 player h and days lost per 1000 contact events) assessed. The two most common events in the match were tackles (221 events per match) and rucks (143 events per match); both of which involve significant impact and physiological strain.

Tackles were also responsible for the greatest loss of time (701.6 days lost per 1000 player h) although their incidence was low (6.1 injuries per 1000 events), with scrums (213.2 days lost per 1000 events) presenting the highest risk per event. The authors summarised by stating that despite the tackle events posing the greatest loss of time, the relatively low incidence rate ultimately resulted in the scrum posing the greatest risk of match injury occurring. Whilst the study of Fuller and colleagues (2007b) provided a useful initial insight into the contact actions in Rugby Union and their propensity to cause injury, there were a number of limitations. For example, whether match contact actions, more specifically the accumulation of key performance indicator variables (such as tackles, tackle assists, contact carries and breakdown entries) have an effect on match injury incidence requires further investigation. Additionally, a more complete and robust statistical analysis (e.g. mixed effect models) should also be adopted (for further details see section 2.5).

All studies exploring Rugby Union and injury incidence to this point in the literature review, have largely reported solely descriptive injury incidence data, associated with matches and training. There have been no measures of load (e.g. sRPE or GPS data) and its potential influence on time-loss incidence. It has been demonstrated how the contact events associated with match play have a propensity to increase the incidence of match injury, although these findings remain speculative. Therefore, a thorough investigation of the effects of match and training load and key performance indicator variables, such as the number of tackles, on time-loss incidence in Rugby Union is warranted.

2.4.3 Playing Surface and Injury

The World has become accustomed to technological advances in almost every single aspect of life. The manufacture of 'sports turf' is no different. An increasing number of competitive professional team sports matches are taking place on fully artificial or hybrid (some artificial content) surfaces. Synthetic playing surfaces have evolved considerably since their initial introduction in the 1960s, with artificial turf routinely installed in professional, university and community sports fields across the world (Drakos et al., 2013). The versality and durability in varying climates make them the ideal surface for multipurpose facilities, yet their health and injury ramifications are yet to be well explored. Research exploring the potential relationships between the incidence of injury on artificial turf compared to natural grass has offered opposing findings. For example, some studies have reported injury incidence to be higher on synthetic surfaces (e.g. Hershman et al., 2012), whilst other have reported no difference when compared to natural grass (e.g. Ekstrand et al., 2006). For example, a study of 290 Footballers from 10 elite European clubs who played their matches on third-generation artificial turf pitch revealed no differences between match injury incidence on artificial turf and grass (19.6 vs. 21.5 per 1000 h, respectively; Ekstrand et al., 2006). On the other hand, a 10-season, study of 5360 National Football League (NFL: American Football) matches, examining all knee and ankle injuries for matches played on either grass or synthetic artificial surface reported that anterior cruciate knee ligament sprains (67% higher on synthetic surface) and ankle eversion injuries (31% higher on synthetic surface) were more prevalent when matches were played on synthetic surfaces compared to natural grass (Hershman et al., 2012). Furthermore, data from 1129 elite association Footballers showed how perceived soreness and pain were both elevated on synthetic turf (Mears et al., 2018). Quantitative data were collected from players across the globe to assess the players concerns regarding the type of playing surfaces. Ninety-one percent of players believed the type of playing surface could increase injury risk, with abrasion injuries, along with soreness and pain perceived to be greater on synthetic pitches (Mears et al., 2018).

A high match injury incidence in Rugby Union has been well established throughout this review of the literature, and with an increasing number of competitive Rugby Union matches taking place on fully synthetic or hybrid (some artificial content) surfaces, the influence of the playing surface on match injury incidence has been questioned (Williams et al., 2016; Ranson et al., 2018). The data accumulated by the English Professional Rugby Injury Surveillance Project over the past five seasons examining match injury incidence on grass compared to artificial turf suggested very little difference in injury incidence between the two different types of surface (81 vs. 77 per 1000 h respectively; England Professional Rugby Injury Surveillance Project, 2018). However, no statistical examination of this data was reported.

Two studies exploring the relationship between playing surface and injury incidence in Rugby Union players both reported no differences between artificial playing surface and injury risk (Williams et al., 2016; Ranson et al., 2018). However, the incidence of lower limb injury, more specifically foot injuries, was higher on synthetic surfaces (synthetic: 3.6 per 1000 h vs. grass: 0.9 per 1000 h). This finding in Rugby Union (Ranson et al., 2018) is in agreement with the findings of the two aforementioned studies in American Football (Thomson et al., 2015; Hershman et al., 2012). It is suggested that an increase in rotational traction on artificial surfaces could be the mechanism behind the increased incidence of lower limb injury on synthetic playing surfaces (Thomson et al., 2010).

Alongside the fully synthetic playing surfaces that have been introduced into professional Rugby Union over the past few years, hybrid pitches (natural grass combined with approximately 3% artificial fibres) have also become more common. The hybrid surface was however excluded from the previous studies exploring injury incidence in Rugby Union, therefore the impact of hybrid surfaces, compared to both natural grass and fully synthetic surfaces, remains unclear.

2.4.4 Training Load and Time-Loss Incidence in Rugby Union

The impact of training (and match) load on time-loss incidence in other team sports has been appraised in section 2.3. As demonstrated in Table 2.8, the assessment of load and its potential relationship with time-loss incidence in Rugby Union has been limited to a single study of 173 professional players from four Premiership clubs (Cross et al., 2016). The internal, subjective training load (sRPE) of players was collated by club's support staff, along with the incidence of training and match injuries over the course of a single season. In-season sRPE load was quantified using multiple methods: absolute cumulative 1, 2, 3, and 4 weekly sums; absolute week-to-week changes in load; weekly training monotony (weekly mean/SD); weekly training strain (weekly training load x training monotony); and the acute:chronic workload ratio (see section 2.3.2.3 for definition). Match load was not entered in any of the load calculations. The effect of weekly load exposure on injury incidence in the subsequent week was assessed.

Results (as demonstrated in Table 2.8) state the odds of sustaining an injury increase by over 50% when 1-week cumulative load exceeds 1245 AU compared to the average training week. A likely harmful effect, via the magnitude-based inference approach, was returned when a change in week-to-week load exceeded 1069 AU. However, when load was quantified using the acute:chronic workload ratio, a 2 SD increase returned what the authors referred to as an unclear finding. However, the non-inclusion of match load, typically the player biggest load of a week seems counterintuitive. Furthermore, assessing injury incidence from a weekly perspective seems unusual. Injury incidence occurs in a single moment, on a specific day, potentially due to the actions of that day or because of the accumulated load over time. Therefore, determining what influence load potentially has on time-loss incidence must happen on a daily, rather than weekly basis, as this is the methods by which load is accumulated. The quantification of load in the long-term through the acute:chronic workload ratio, the exponentially weighted moving average and cumulative 1, 2, 3, and 4 weekly sums methods is justified, however the precise impact must be taken from a snapshot of the state of load, on the specific day of time-loss occurrence. This can be achieved, for example, through absolute daily load or the exponentially weighted moving average value for the day of event occurred. Additionally, the mismanagement of load has the potential to not only contribute to injury occurrence but also the onset of illness (Foster, 1998). Therefore, models seeking to identify relationships between match and training load and injury occurrence should include illness as potential effect of match and training load. Therefore, the focus of this thesis will not only be exploring the effect of match and training load on injury incidence, but also that of illness, henceforth the time-loss incidence definition (injury or illness).

Table 2.8, reviewing literature associated with injury incidence in Rugby Union, portrays the steady increase over time in injury incidence rates in matches and training from an initial rate of 69.0 per 1000 match h (Bathgate et al., 2002) and 2.0 per 1000 training h (Brooks et al., 2005b), to the 101.7 per 1000 match h and 3.3 per 1000 training h stated by Cross and colleagues (2016). This increased injury incidence in both matches and training overtime reaffirms the requirement for a thorough investigation into the relationships between load and injury incidence in elite Rugby Union. Subsequently, a clear requirement for management protocols to decrease the 'risk' of time-loss incidence is required. Only one study to date, Cross and colleagues, 2016, has broadly explored the impact of training load on injury incidence. In the case of Cross and colleagues (2016), purely subjective load measures (sRPE) quantified using the absolute and acute:chronic workload ratio methods of load quantification were adopted. Therefore, not only is the requirement for objective loads to be explored, but also the newly suggested exponentially weighted moving average, a potentially more sensitive measure of load quantification (Murray et al., 2017), necessary. The inclusion of match load, illnesses and the observation of time-loss incidence on a daily, not weekly basis, is required. The positional demand differences of Rugby Union players have been outlined in section 2.2, especially in matches (Lindsay et al., 2015), therefore a thorough investigation into the factors affecting time-loss incidence in these two positional groups is required. Although no study has yet sought to identify physical differences between the players of the Premiership and Championship (top two tiers of professional Rugby Union in England), by virtue of the higher playing division, the players operating in the Premiership may be physically superior to those in the Championship and therefore produce higher speed / power outputs than that of their Championship counterparts. Consequently, the impact of this on time-loss incidence has not been considered. The unique opportunity to examine the influence of load on both incidence and severity of time-loss incidence in the top two tiers of professional Rugby Union in England presented itself in this thesis.

2.4.5 Summary of Load and Time-Loss Incidence in Rugby Union

It has been well documented through this review of the literature that Rugby Union, a sport built on its running demands and contact actions has a high incidence of match injury in comparison to other team sports. The propensity for contact actions to contribute heavily towards the high match injury incidence rates alongside the introduction of innovative playing surfaces (hybrid and synthetic) both require further investigation at elite domestic level. The role match and training load management has on the potential to minimise the likelihood of time-loss incidence occurrence has been demonstrated across a number of elite sporting populations (Rogalski et al., 2013; Colby et al., 2014; Carey et al., 2017; Bowen et al., 2017; Murray et al., 2017). However, the sport of Rugby Union has not been well researched in this area (only study to date: Cross et al., 2016). The requirement for models comprising both objective and subjective measures of load, alongside a plethora of quantification methods (absolute, ACWR, EWMA, cumulative 1, 2, 3, and 4 weekly sums) is necessary. Moreover, the role of match and training load at explaining the variance in likelihood of sustaining a major severity time-loss incidence compared to a minor severity time-loss incidence, has not been considered. This will not only provide researchers with knowledge, but also applied practitioners with a complete understanding of the methods by which load can be monitored and also the best approaches to incorporate into load management processes to reduce the likelihood of sustaining major severity, time-loss incidences; ultimately enhancing team performance.

2.5 Statistical Analyses in Longitudinal Load : Injury Studies

As a direct result of technological advancements, the availability of complex statistical approaches to analyse large datasets has increased. By repeatedly collecting data on the same individuals over time, researchers are able to collate longitudinal datasets to answer complex research questions regarding occurrences that change and fluctuate over time. In a landmark article by Professor Linda Collins, it was described how aligning the (1) theoretical model, (2) temporal design and (3) the statistical model is crucial when analysing longitudinal datasets (Collins et al., 2006). An example of the application of these three concepts is: (1) if researchers theorise that a given physiological variable fluctuates every hour, (2) data must be collected at least on an hourly basis and then (3) researchers must select a statistical model that enables them to examine the relationship between these fluctuations and the outcome of interest. Collins noted that perfect alignment of these three components is not always possible, but it does provide the researcher a target and the readers a lens through which longitudinal research can be evaluated (Collins et al., 2006).

The field of sport and exercise science provides one example of the type of study which adopts a longitudinal approach to data collection. The questions to be posed in this thesis are reliant upon the three points raised (1: theoretical model; 2: temporal design; 3: statistical model). For example, when examining the influence of match and training load on time-loss incidence:

1. Theoretical model: it is theorised that match and training load fluctuates daily.
2. Temporal design: match and training load is collected on a daily basis.
3. Statistical model: to analyse the relationship between fluctuations in match and training load and time-loss incidence occurrence.

This approach can be utilised across all of the research questions posed in this thesis.

The methodologies, and more specifically the statistical methods used, in 34 studies exploring the load : injury relationship across multiple sports, study lengths, subject n and level of competition was systematically examined by Windt et al. (2018). All studies included in the review met the three step criteria outlined by Collins and therefore authors focused on assessing the different types of statistical analysis used in each study and, more specifically, whether they adequately addressed the research question. It was concluded that time-to-event analyses (e.g. Cox proportional hazards and frailty models) and multilevel modelling are best suited for longitudinal datasets. However, fewer than 10% of the studies examined in the review used either of these methods (n = 3). Choosing a statistical model that closely aligns with the theoretical underpinning and addresses the challenges posed by longitudinal data is clear. Multilevel modelling is an example of a statistical approach that meets these criteria (Windt et al., 2018). The statistical analysis method used in the load : injury relationship studies examined in this review of literature can be found in Table 2.9. Of the ten studies discussed in this literature review, 8 out of the 10 studies used some form of regression model, with only 1 out of the 10 studies adopting a frailty model (one of the time-to-event analyses best suited for longitudinal datasets). Therefore, it clearly demonstrates the limitations surrounding the statistical analysis methods used in the studies to date, with only one study using an approach deemed appropriate based on the review of Windt et al. (2018).

Therefore, all statistical analyses undertaken in this thesis, which has constructs similar to that posed by Collins et al. (2006), will adopt a multilevel modelling approach. Mixed effect models reduce the risk of false-positive associations and have an applied correction method that increases the power of the analysis (Yang et al., 2014). Furthermore, mixed effect models allow for individual level effects, such as position (forward or back) and season (Premiership or Championship), which can subsequently be entered as a fixed effect variable. In summary, the challenges associated with longitudinal data statistical analysis can be addressed by undertaking mixed effect models. Subsequently, the implementation of robust statistical methods will be used throughout this thesis.

Table 2.9. A review of the statistical analysis methods used in the load : injury relationship studies appraised in the literature review.

Author and Year	Level of Competition	Number of Explanatory Variables	Statistical Analysis Technique	Other
Anderson et al. (2003)	Collegiate	3	Pearson correlation	
Dennis et al. (2003)	Elite	2	Paired and independent samples T-tests	
Gabbett and Domrow (2007)	Elite	1	Regression (logistic – regular) Regression (linear)	Logistic = individual player analysis Linear = team analysis
Gabbett and Ullah (2012)	Elite	13	Frailty model	
Rogalski et al. (2013)	Elite	5	Regression (logistic – regular)	
Colby et al. (2014)	Elite	30	Regression (multinomial – regular)	
Hulin et al. (2014)	Elite	6	Regression (logistic – regular)	
Cross et al. (2016)	Elite	8	Regression (generalised estimating equations)	
Carey et al. (2017)	Elite	336	Regression (quadratic)	
Bowen et al. (2017)	Elite Youth	20	Regression (logistic – regular)	
Murray et al. (2017)	Elite	12	Regression (logistic – regular)	

2.6 Recommendations for Future Research Investigating the Demands and Load of Elite Rugby Union

From reviewing the literature to date, recommendations for future research investigating the demands and load of elite Rugby Union and its influence on the incidence and severity of time-loss occurrence can be made. These include the investigation of both match and training load in elite domestic English competition, incorporating both running load and key performance indicator demand data., and a comparison between the top two tiers of competition in England (Premiership and Championship). Such work will allow practitioners to adequately prepare players in training, for the match demands they will be exposed to on match days, reduce time-loss incidence occurrence and ultimately improve performance.

The propensity for match injury as a direct consequence of the physical nature of Rugby Union warrants further investigation, specifically through a robust statistical analysis model, such as multilevel modelling. Moreover, with the advancement of 'sport turf' manufacturing, an increasing number of competitive Rugby Union matches are taking place on surfaces containing artificial content. The hybrid (3% artificial) and synthetic (100% artificial) surfaces are commonly seen across Premiership and Championship fixtures and the influence of these surfaces on the likelihood of match injury remains unclear and has so far neglected the hybrid surface.

Finally, the influence of match and training load on the likelihood of time-loss incidence occurrence has been demonstrated across as number of team sports. However, its effect in Rugby Union players has not been well considered. Objective and subjective measures of match and training load and the numerous methods of quantification have not been examined in the literature to date. Furthermore, the ability for match and training load to explain the variance in likelihood of sustaining a major severity time-loss incidence over one of minor severity is entirely unexplored.

Therefore, the aims of the series of studies presented in this thesis are:

- To assess the match and training demands in elite Rugby Union, incorporating both running load and key performance indicator actions across the top two tiers of competition in England (Chapter IV);
- The examination of match key performance indicator variables (e.g. number of tackles made) and its propensity to influence match injury incidence in elite Rugby Union (Chapter V);
- To examine the effect of playing surface (grass, hybrid and synthetic) on the incidence of match injury in elite Rugby Union (Chapter VI);
- To examine the influence of match and training load exposure on time-loss incidence in elite Rugby Union players (Chapter VII);
- To consider which measures of training and match load (sRPE load, distance and high-speed running distance) and which quantification method (absolute, acute:chronic workload ratio, exponentially weighted moving average and 7, 14, 21, and 28 d cumulative sums) best explain the variance in time-loss incidence occurrence in elite Rugby Union players (Chapter VII);
- To investigate which match and training load variable best explains the variance in the severity of time-loss incidence occurrence (Chapter VIII).

Chapter III
General Methods

3.1 Introduction

This chapter provides an account of the general methodologies used throughout the studies presented in this thesis (chapters IV – VIII) and is split into six sections. The first section (section 3.2) outlines the study cohort used throughout the experimental chapters. The second section (section 3.3) outlines the different measures of match and training load used throughout each of the studies. The third section (section 3.4) outlines the quantification methods used for the aforementioned training and match load variables. The fourth section (section 3.5) defines time-loss incidence (injury and illness), the site of injuries, severity definitions, modality of injury incidence and sessions in which the injury may occur used throughout the analyses of the experimental chapters. The fifth section (section 3.6) details the key performance indicator variables used to count the contact actions during Rugby Union matches. The final section (section 3.7) outlines the statistical analysis that was conducted on the data collected.

3.2 Study Cohort

The participants in this thesis were a cohort of 89 elite Rugby Union players (age: 26.5 ± 4.5 years; height: 1.86 ± 0.07 m; body mass: 104.3 ± 13.5 kg), registered to the first team squad of an English Club during the 2016-17 and 2017-18 professional Rugby Union seasons. A total of 60 players during the 2016-17 season and 56 players during the 2017-18 seasons, with 63 players completing a single season and 26 players completing both seasons. One season examined the Premiership and the other examined the Championship. Ethical approval was provided by the host institution's ethical advisory committee for all studies and all players provided their written consent to participate.

For the purpose of this thesis, the summed forward and back positional groups will be used. In total 51 forwards and 38 backs make up the 89 players assembling in the experimental chapters (IV – VIII). The playing positions of Rugby Union can be broken down in to forwards and backs as follows:

Table 3.1. Positional groups of Rugby Union.

Forwards	Backs
(1) Loose-head prop	(9) Scrum-half
(2) Hooker	(10) Fly-half
(3) Tighthead prop	(11) Left wing
(4) Left second row	(12) Inside centre
(5) Right second row	(13) Outside centre
(6) Blindside flanker	(14) Right wing
(7) Openside flanker	(15) Fullback
(8) Number 8	

3.3 Match and Training Load

Load is a measure of physiological stress placed on the human anatomy including the neuroendocrine, immunological, cardiovascular and musculoskeletal systems (Adams and Kirkby, 2001). The term "workload" has been frequently used in the field of sport and exercise science for a number of years. However, its shortcomings, initially highlighted by Knuttgen (1978) is still commonly though erroneously used today (Winter, 2006). The term "workload", according to Winter (2006) does not match the principles of the Systeme International d'Unites (SI) for a number of reasons detailed in the editorial: Winter (2006); "workload" – time to abandon? Therefore, for the purpose of this thesis the term 'match and training load' encapsulates the 'load' definition outlined above (Adams and Kirkby, 2001).

Match and training load can be measured primarily through two means; external or internal.

Table 3.2. Definitions of external and internal load.

Load Measure	Sport Example	Rugby Union Example
External	Mean cycling power output sustained over a set period of time (i.e. 400 W for 30 min).	Total distance covered during a match or training session
Internal	Mean heart rate over the course of a 10 km steady-state WattBike session	Rating of perceived exertion following a match or training session

Another aspect of the load monitoring process that works in conjunction with the external/internal load profile, is whether the particular variable of interest is objective or subjective. Objective measurements, such as distance run and heart rate, have minimal subjective influence. Subjective measurements refer to the data derived from the athlete's personal feelings, perspectives and opinions (Coyne et al., 2018).

For the purpose of this thesis, session ratings of perceived exertion (sRPE) provides the subjective measure of load and global positioning system (GPS) data provides the objective measures. Therefore, over the course of this thesis training and match load with be quantified through both measures, subsequently providing a novel aspect within this area of research.

3.3.1 Rating of Perceived Exertion

3.3.1.1 Definition of Rating of Perceived Exertion

A rating of perceived exertion (RPE) is a subjective measure of load derived through the modified Borg CR-10-point RPE scale, detailed in the collection protocol below.

RPE (Rating of Perceived Exertion).	
Rating.	**Description.**
0	Nothing At All.
1	Very Light.
2	Fairly Light.
3	Moderate.
4	Somewhat Hard.
5	Hard.
6	
7	Very Hard.
8	
9	
10	Very, Very Hard (Maximal).

Figure 3.1. The modified Borg CR-10 rating of perceived exertion (RPE) scale.

3.3.1.2 Rating of Perceived Exertion Collection Protocol

For every field- and gym-based training session and match, an RPE rating for each player, using the modified Borg CR-10-point RPE scale (Foster et al., 2001), was obtained within 30 min of the end of the training session and/or match, in line with recommendations (Kraft et al., 2014). Session RPE (sRPE) load was then calculated as follows:

sRPE load (AU) = RPE x session duration (min)

(Foster et al., 2001) (see section 3.4: load quantification methods, for additional detail).

The validity and reliability of the sRPE load measure has been demonstrated previously (Gabbett and Domrow, 2007; Foster et al., 2001). Specifically, sRPE load has strong correlations with heart rate response and blood lactate concentration in order to subsequently estimate relative exercise intensity. The relationship between sRPE and estimating relative exercise intensity has been demonstrated during typical Rugby League training activities, returning positive correlations of 0.89 and 0.86 with heart rate and blood lactate concentrations (Gabbett and Domrow, 2007).

3.3.2 Global Positioning System

3.3.2.1 Definition of Global Positioning System

The global positioning system (GPS) is a suite of satellites, orbiting 20,200 km above the Earth, providing precise time and positioning information to receivers on the ground, at sea, in the air and the crew of the International Space Station (Aughey, 2011). GPS operates worldwide and can be used for numerous functions and utilities. Its origins were conceived for military and commercial use in the late 1970's and it has since become a standard piece of technology, embedded within smartphones which define social life in the twenty-first century. It is frequently used as an objective measure of load across almost all elite sporting environments (Gabbett and Ullah, 2012; Colby et al., 2014; Carey et al., 2017; Bowen et al., 2017; Murray et al., 2017).

3.3.2.2 Global Positioning System Data Collection Protocol

Over the course of the two-year data collection process, three GPS hardware and software systems were used; Catapult Sprint OptimEye S5 Monitoring System (Canberra, Australia), GPSports Monitoring System (Canberra, Australia) and STATSports Apex Monitoring System (Newry, Northern Ireland).

Each player involved in a given training session or match wore a GPS unit in accordance to the manufacturer's guidelines. The GPS unit was to be worn in the specifically designed GPS unit vest which places the unit on the upper back between the scapulae and to be turned on 15 minutes before the start of any training session or match to ensure a strong GPS connection is made with the satellites before any activity is undertaken. It was then downloaded and analysed within the applicable software and exported into Microsoft Excel for further analysis and cleaning prior to the statistical analysis procedures.

The GPS data is able to provide numerous variables such as; total distance covered, the distance covered at varying speeds (low-speed running distance, moderate-speed running distance, high-speed running distance) as well as a number of additional variables not used within this thesis, but may be of use for applied practitioners.

Variables included for analysis within this thesis were total distance (m) and high-speed running distance (m). High-speed running distance was specified as the distance covered at greater than 70% of an individual player's maximum velocity, determined during pre-season testing (40 m sprint testing) and updated if bettered at any stage across the season; thus providing an individualised approach relative to the maximum running speeds of each player. When multiple sessions occurred in a single day, the distances and high-speed running distances across sessions were aggregated to provide a single value for each variable per day of the season.

3.3.2.3 Global Positioning System Validity and Reliability

The number of satellites was satisfactory on all days for all systems, with an average of 9 ± 1 satellites per day being used and a horizontal dilution of precision of 0.58 ± 0.06. Previous research has demonstrated the reliability and validity of each of the GPS systems used, as follows:

GPSports SPI-Pro (5 Hz): Waldron et al. (2011) completed a study examining the validity and test-retest reliability of the GPSports SPI-Pro (5 Hz) unit when compared to speed timing gates. They demonstrated that GPS measurements were reliable for all variables of distance and speed (coefficient of variation (CV) = 1.62% to 2.30%), particularly peak speed (95% limits of agreement (LOA) = 0.00 ± 0.8 $km \cdot h^{-1}$; CV = 0.78%).

Catapult OptimEye S5 (10 Hz): Thornton et al. (2018) assessed the inter-unit reliability of three different GPS units, the Catapult S5 (10 Hz) being one of those examined. The main findings demonstrated the reliability was good (CV = 0.20 ± 1.50%) for distance, speed and maximum velocity. Overall, the findings suggested that the GPS device demonstrated acceptable reliability when quantifying distances, speed and average acceleration regardless of processing method (Thornton et al., 2018).

STATSports APEX (10 Hz): Beato et al. (2018) investigated the validity of the STATSports Apex (10 Hz) GPS unit for measuring distance and maximum speed outcomes. Results showed that the APEX unit provided good levels of accuracy for distance (1.05 ± 0.87% bias) and for maximum speed (2.36 ± 1.67% bias), with non-significant differences from the ground truth reference and gold standard criterion device for both distance and speed respectively.

A small supplementary validity assessment, in addition to those described above, was undertaken on a single player, in a single session to test the inter-unit reliability between all three GPS devices. The player wore all three GPS units in three GPS vests next to each other at the same time for a single training session with the data derived from the units outlined in Table 3.3. As demonstrated, the inter-unit validity was good, with high levels of accuracy, with a less than 2.0 % difference in both distance and high-speed running distance between the three units.

Table 3.3. The data derived from the three GPS units to assess the inter-unit validity from the in-house assessment.

GPS System	Distance (m)	High-Speed Running Distance (m)
STATSports APEX (10 Hz)	3744	52
Catapult OptimEye S5 (10 Hz)	3752	52
GPSports SPI-Pro (5 Hz)	3738	51

The proprietary software derived data for all three GPS models and the firmware and software were not updated across the entire study period. In an ideal scenario, all players would have worn identical GPS units for the entire study period. However, due to practical constraints this was not possible. Therefore, to counteract this each player was not only measured using the same system but also wore exactly the same GPS unit (within that system) across the study period, for all matches and training sessions. The change of head coach and support staff between seasons resulted in increased funding being available and subsequently the purchase of a large quantity of GPS units (STATSports APEX) meant all players in the second season were able to use the same manufacture of GPS unit.

3.4 Load Quantification Methods

Match and training load derived through both subjective (session RPE load) and objective (GPS; total distance and high-speed running distance) measures can then be quantified through different methods for further analysis (e.g. assessing the influence of match and training load on time-loss incidence occurrence). The additional quantification methods add an extra dimension to the load monitoring process by providing longer-term perspective on the load accumulation. The four quantification methods explored in this thesis are: absolute match and training load; acute:chronic workload ratio; exponentially weighted moving average; cumulative 7, 14, 21, and 28 d rolling sums.

3.4.1 Absolute Load

Absolute load details the total amount of load, either sRPE load, distance or high-speed running distance, accumulated on that particular day.

An example of this for sRPE load, for a training session lasting 60 minutes at an RPE of 5:

$$5 * 60 = 300 \text{ AU.}$$

For distance and high-speed running distance, the distance covered in metres (m) for a particular training session or match, summed for that day.

This method of load quantification is applied to all three load measures in experimental chapters IV - VIII, giving rise to the variables absolute sRPE load, absolute distance and absolute high-speed running distance.

3.4.2 Acute:Chronic Workload Ratio

The acute:chronic workload ratio (ACWR) is the ratio of the average load in the past 7 days (acute) compared to the average load in the past 28 days (chronic) (Blanch and Gabbett, 2016). The acute 7-day period is also included as part of the chronic 28-day period.

Specifically, the acute:chronic workload ratio for any given day is calculated by:

Past 7-day period (1 – 7) = W1 (2500 AU)
The days previous (8 – 14) = W2 (2100 AU)
The days previous (15 – 21) = W3 (2400 AU)
The days previous (22 – 28) = W4 (2200 AU)

Acute = W1 (2500 AU)

Chronic = W1 + W2 + W3 + W4 / 4
(2500 AU + 2100 AU + 2400 AU + 2200 AU = 9200 AU)
(9200 AU / 4 = 2300 AU)

Acute:Chronic = 2500 AU / 2300 AU = 1.09

This method of load quantification is applied to all three load measures in experimental chapters IV - VIII. Giving rise to the variables ACWR sRPE load, ACWR distance and ACWR high-speed running distance.

3.4.3 Exponentially Weighted Moving Average

As detailed in chapter II, in more recent year's researchers have questioned the acute:chronic workload ratio method, most notably the issues with mathematical coupling of the acute:chronic workload ratio method (Williams et al, 2017; Menaspa, 2017; Lolli et al, 2017; Drew and Pudram, 2016). This subsequently led to the suggestion of a new approach to load quantification by placing extra emphasis in the load accumulated in the most recent days (compared to the preceding days/weeks), subsequently mitigating the mathematical coupling issues with the acute:chronic workload ratio approach and addressing the concerns surrounding the decaying nature of fitness and fatigue overtime.

Specifically, the exponentially weighted moving average for any given day is calculated by:

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

where λ_a is a value between 0 and 1 that represents the degree of decay, with higher values discounting the older observations at a faster rate. The λ_a is given by:

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

where N is the chosen time decay constant, typically 7 days for the acute and 28 days for the chronic.

Subsequently, the EWMA is then calculated as:

$$EWMA = \frac{\text{acute } EWMA_{today}}{\text{chronic } EWMA_{today}}$$

This method of load quantification is applied to all three load measures in experimental chapters IV - VIII, giving rise to the variables EWMA sRPE load, EWMA distance and EWMA high-speed running distance.

3.4.4 Cumulative Rolling Sums

The absolute match and training load variables can also be accumulated over rolling weeks (i.e. the rolling 7, 14, 21, and 28 d cumulative sums). The previous, 7, 14, 21, and 28 d cumulative load was therefore calculated on each day.

This method of load quantification is applied to all three load measures in experimental chapters IV - VIII, giving rise to the variables 7, 14, 21, and 28 d sRPE load, 7, 14, 21, and 28 d distance and 7, 14, 21, and 28 d high-speed running distance.

Table 3.4. Example data set of absolute, acute:chronic workload ratio and exponentially weighted moving average load variables.

ID	Day	sRPE load	ACWR sRPE load	EWMA sRPE load	Distance	ACWR distance	EWMA distance	HSR distance	ACWR HSR distance	EWMA HSR distance
11	69	938	0.80	1.18	5736	0.74	1.10	25	0.73	1.03
11	70	0	0.80	0.95	0	0.74	0.88	0	0.73	0.83
11	71	279	0.91	0.97	3385	0.90	1.01	13	0.81	0.83
11	72	632	1.08	1.19	6687	1.18	1.32	50	1.07	1.21
11	73	0	1.08	0.96	0	1.18	1.06	0	1.07	0.98
11	74	432	1.02	1.07	5215	1.13	1.24	26	0.79	1.07
11	75	0	1.09	0.86	0	1.13	1.00	0	0.76	0.86
11	76	31	0.70	0.72	1106	0.95	0.90	0	0.71	0.69
11	77	754	0.99	1.13	5629	1.18	1.16	61	1.07	1.24
11	78	0	0.97	0.91	0	1.12	0.94	0	1.09	1.00
11	79	227	0.82	0.91	3704	0.96	1.05	14	1.07	0.97

Key. ACWR: acute:chronic workload ratio; EWMA: exponentially weighted moving average; HSR: high-speed running.

Table 3.5. Example data set of the rolling 7, 14, 21, and 28 d cumulative sums.

ID	Day	sRPE load 7 d	sRPE load 14 d	sRPE load 21 d	sRPE load 28 d	Distance 7 d	Distance 14 d	Distance 21 d	Distance 28 d	HSR dist. 7 d	HSR dist. 14 d	HSR dist. 21 d	HSR dist. 28 d
11	69	1539	3412	6431	7724	11687	27197	52900	63582	99	161	413	542
11	70	1539	3412	6431	7724	11687	27197	52900	63582	99	161	413	542
11	71	1818	3365	5793	8003	15072	25830	47977	66967	112	157	368	555
11	72	2330	3171	5567	8635	21759	26593	49317	73654	162	185	275	605
11	73	2330	3171	5567	8635	21759	26593	49317	73654	162	185	275	605
11	74	2313	2882	5349	9067	22201	26974	48487	78869	125	188	296	631
11	75	2281	2882	5331	8377	21023	26974	47469	74604	114	188	296	601
11	76	1374	2913	4786	7805	16393	28080	43590	69293	89	188	250	502
11	77	2128	3667	5540	8559	22022	33709	49219	74922	150	249	311	563
11	78	1849	3667	5214	7642	18637	33709	44467	66614	137	249	294	505
11	79	1444	3774	4615	7011	15654	37413	42247	64971	101	263	286	376

Key. HSR dist.: high-speed running distance.

3.5 Time-Loss Incidence

3.5.1 Definition of Time-Loss Incidence

Time-loss incidence is defined as any physical complaint experienced by an athlete which results in that individual be unable to complete training or match play for a period of greater than 24 hours (Fuller et al., 2007a). Time-loss incidence can thus be as a result of injury or illness, given that both may prevent the player from participating in scheduled training or match play.

For the purpose of this thesis, the time-loss incidence definition falls in line with the consensus statement detailed by the International Rugby Board (IRB) in 2007 (Fuller et al., 2007a).

3.5.2 Site of Time-Loss Incidence

The site of time-loss incidence was recorded for every injury raised by a player in alignment with the consensus statement detailed above (Fuller et al., 2007a). A total of 19 sites are put forward by the IRB for injury definition:

- Head/face
- Neck/cervical spine
- Sternum/ribs/upper back
- Abdomen
- Lower back (lumbar spine)
- Sacrum/pelvis
- Shoulder/clavicle (incl. ACJ)
- Upper arm
- Elbow
- Forearm
- Wrist
- Hand/finger/thumb
- Hip/groin/adductor
- Anterior thigh (quadriceps)
- Posterior thigh (hamstring)
- Knee
- Lower leg/Achilles tendon (incl. gastrocnemius)
- Ankle
- Foot/toe

An additional twentieth site has been included for the purpose of this thesis, to complete the time-loss incidence definition.

- Illness.

3.5.3 Severity Definitions

The severity of each time-loss incidence sustained was also recorded, again in alignment with the IRB statement (Fuller et al., 2007a). Severity was calculated as the days lost from competition and training from the date of injury or illness until the date of the players' return to full participation in team training and availability for match selection was reached.

The severity of time-loss incidence was categorised as either minor (≤7 d) or major (≥8 d) based on the work of Brooks et al. (2005a), to ensure consistency with Rugby Union literature. Each time-loss incidence (and its related severity (minor or major)) was entered into the dataset for the day on which it occurred and was subsequently associated with the absolute, acute:chronic workload ratio, exponentially weighted moving average or cumulative rolling sum match and training load for that day for chapter VIII. Additionally, match injury and their associated severities for the key performance indicator variables and pitch type analysis of chapters V and VI.

3.5.4 Modalities of Injury Incidence

The modality by which each time-loss incidence occurred was recorded for additional analyses. Injuries were classified according to the consensus statement detailed above (Fuller et al., 2007a); whether they were as a result of contact with another player or object or were a non-contact injury. The following three categories were used:

- Contact
- Non-contact
- Illness.

3.5.5 Session of Injury Incidence

The session in which each time-loss incidence occurred was recorded for additional analyses. Injuries were classified according to the consensus statement detailed above (Fuller et al., 2007a); whether they occurred during match play or a training session. The following three categories were used:

- Match
- Training
- Illness.

3.6 Key Performance Indicator Variables

3.6.1 Definition of Key Performance Indicator Variables

Rugby Union is a high-intensity sport categorised by not only bouts of near maximal high-speed running demands but also high-intensity collisions / contacts. The physical demands of Rugby Union have been reported using video-based time motion analysis with the contact actions most commonly assessed using notational analysis. For the purpose of this thesis the following variables, which best quantify the contact actions associated with Rugby Union (Fuller et al., 2007a), were coded as follows:

- *Tackles*: all first up tackles made by an individual player
- *Tackle assists*: all tackles made by an individual player where they were not the first player into that particular tackle scenario (secondary, tertiary tackler)
- *Tackles missed*: all tackles attempted by an individual player but where the player failed to effectively stop the opposing player and perform a completed tackle scenario
- *Contact carries*: all carries made by an individual player where they took the ball into contact / collision
- *Breakdown entries*: all breakdown entries by an individual player, on either the attacking (e.g. cleaner) or defending (e.g. jackler) side of the ruck
- *Contact events*: a sum of the above five variables to provide a total count of contact / sport specific actions.

3.6.2 Key Performance Indicator Data Collection Protocol

For all first team league matches, the key performance indicator variables were coded by the club's performance analyst. All variables were coded by the same performance analyst for the two-seasons of data collection to ensure consistency between matches using performance analytics software (Sportscode Version 11, Hudl, Lincoln, Nebraska).

3.7 Statistical Analysis

As covered in more detail in the chapter II: review of the literature; mixed effect models have been demonstrated to be the most effective methods of statistical analysis for longitudinal load : time-loss incidence relationship studies.

All statistical analysis was undertaken using R software package (www.r-project.org, version 3.6.1). Mixed effect variables were used throughout every experimental chapter with the *lme* (linear mixed effect) and *glmer* (generalised linear mixed effect) the most commonly used R functions. The exact models used, distribution dependency and the subsequent transformations are explained in the statistical analysis section of each chapter.

Chapter IV
Training and Match Demands of Elite Rugby Union

4.1 Introduction

Rugby Union is an intermittent team sport, where shorts periods of maximal or high-speed running exercise are punctuated by lower intensity exercise or rest (Nicholas, 1997). The sport is estimated to have more than 6.6 million participants Worldwide and a quadrennial World cup consisting of 20 nations attracts over 4 billion viewers; therefore, Rugby Union has a nationally and internationally significant presence (World Rugby, 2020). The top two leagues of Rugby Union in England are classified as professional (Premiership and Championship), each comprising 12 teams (England Rugby, 2020).

A number of studies have attempted to quantify the physical demands of Rugby Union, predominantly through the use of time-motion analysis and global positioning systems (GPS) (Duthie et al., 2003; Roberts et al., 2008; Cunniffe et al., 2009; Hartwig et al., 2011; Coughlan et al., 2011; Cahill et al., 2013). The initial work exploring the match demands was undertaken using time-motion analysis, a non-intrusive method of video analysis allowing information about players' movement patterns (e.g. total distance covered and number of sprints). For example, 29 English Premiership Rugby Union players were monitored during five leagues matches across the 2002-2003 and 2003-2004 seasons (Roberts et al., 2008). To allow for inter-positional observations the players were divided into forwards and backs, a common classification in Rugby Union due to the (assumed) different nature of match play between these positions. Results demonstrated that the backs (6127 ± 724 m) covered more total distance than the forwards (5581 ± 692 m), also covering a greater distance at higher speeds of 5.0-6.7 $m{\cdot}s^{-1}$ (backs: 448 ± 149 m; forwards: 297 ± 107 m) (Roberts et al., 2008). Whilst this study provides a useful initial insight, the data were normalised to a full 80 min based on the data collected in the second and third quarters (20-60 min) of the matches. However, this approach is questionable given that the first 20 min and last 20 min are when the players are likely to be at their 'freshest' and most fatigued respectively, and thus their movement patterns may be significantly different to the observed period (20-60 min) of the match. The lack of relative speed classifications (i.e. all players performance was evaluated using the same absolute thresholds) is a further limitation given that the true maximum speeds will vary considerably between players (and likely between forwards and backs in particular). Therefore, utilising a relative approach to high-speed running threshold (e.g. greater than *x*% of an individual's maximum speed) may provide further insight into the positional demands associated with Rugby Union match play (Reardon et al., 2015; Gabbett, 2015). It is also important to consider that such time-motion analysis procedures have proven to be very time consuming and costly, thus limiting their practical utility (Roberts et al., 2008).

The most comprehensive paper to date to analyse the demands of Rugby Union match play in the English Premiership used GPS technology (Cahill et al., 2013). Eight professional clubs from the English Premiership in the 2010-2011 season took part in the study. The total distance covered and relative distance ($m \cdot min^{-1}$; measured relative to the time spent on the pitch) covered per match per player were calculated along with maximum speed, average speed and the time spent at different speed intensities relative to that player's maximum velocity (using the criteria of Venter et al. (2011)). The most noteworthy characteristics of the movement patterns underpinning the two positional groups were that the backs moved predominantly (46.3%) in the lowest speed category (<20% of maximum speed) whereas the forwards covered most of their distance (46.2%) whilst jogging (20-50% of maximum speed). The backs covered a greater total distance (6545 m vs. 5850 m), greater total distance per minute (71.1 $m \cdot min^{-1}$ vs. 64.6 $m \cdot min^{-1}$) and had a higher maximum speed (8.5 $m \cdot s^{-1}$ vs. 7.3 $m \cdot s^{-1}$) when compared to forwards. However, a significant omission from these studies is that they make no reference to the training demands associated with Rugby Union.

The only insight that we have regarding the training demands of Rugby Union comes from comparing training and match demands in male adolescent players using time-motion analyses (Hartwig et al., 2011). Their main finding demonstrated the disparity between physical match demands and on-field training demands in adolescent players, where the total distance, time spent jogging, time spent striding and time spent sprinting were all observed to be greater in matches compared to training. However, this study was in adolescent players and its relevance to other levels and the professional game in particular is unclear. Furthermore, no study to date has considered the subjective load demands of both training and matches in Rugby Union, despite the demonstrated utility of this method in assisting with the moderation of load management for both performance enhancement and injury / illness prevention (Coyne et al., 2018).

A further limitation of studies to date is that they have only considered a limited number of variables such as the distance covered, and distance covered at high speed. Another important determinant of the demands of Rugby Union are key performance indicators, such as the number of tackles made, and ball carries completed (Lindsay et al., 2015). These key performance indicators have not been studied in terms of the demands of Rugby Union. Furthermore, it is not known whether the demands of Rugby Union differ between the very highest level of competition (i.e. Premiership) and the second tier (i.e. Championship); where the difference in standard could well affect the demands placed upon players.

Therefore, the aims of this study were to examine and identify the training and match demands associated with professional Rugby Union. In addition to quantifying the overall demands, the study also sought to identify the influence of position (forward/back) and the league of competition (Premiership/Championship) on objective (GPS) and subjective (sRPE) demands, as well as the key performance indicators (e.g. the number of tackles). The study followed a professional Rugby Union team that, across two seasons, played in both levels of competition and thus, allows a unique comparison between these leagues of play within the same club.

4.2 Methodology

4.2.1 Study Design

The cohort of Rugby Union players examined in this study is consistent with the other chapters presented in this thesis (n = 89). Participant characteristics can be found in the general methods (Chapter III). In brief, all training sessions and matches were monitored using both subjective (session ratings of perceived exertion (sRPE) and objective (GPS) load data. In addition, key performance indicator variables, such as the number of tackles made and number of carries, were analysed in matches.

4.2.2 Rating of Perceived Exertion (RPE)

For every field-based training session and match, an RPE rating, using the modified Borg CR-10 RPE scale (Foster et al., 2001), was obtained within 30 min of the end of the exercise, in line with the recommendations of Kraft et al. (2014). Session RPE load (sRPE load) in arbitrary units (AU) was then calculated for each player by multiplying the given RPE by the session duration (min) (Foster et al., 2001). This was performed for all players across both seasons of data collection. The collection of RPE data was consistent across all experimental chapters and additional information on the validity and reliability of sRPE for estimating relative exercise intensity can be found in the general methods (Chapter III).

4.2.3 Global Positioning Systems (GPS)

An objective measure of match and training load was obtained through GPS for every field-based training session and match. The assignment, validity and reliability, software and horizontal dilution of precision information of the GPS data collection can be found in the general methods (Chapter III). Total distance and high-speed running distance (set at greater than 70% of an individual player's maximum velocity) were the two objective GPS-derived variables used throughout this study. Additional information on the determination of high-speed running threshold can be found in the general methods (Chapter III).

4.2.4 Key Performance Indicators

For all first team league matches (Premiership and Championship) a host of key performance indicator variables were coded by the club's performance analyst. All variables were coded by the same performance analyst to ensure consistency between matches using performance analytics software (Sportscode Version 11, Hudl, Lincoln, Nebraska). The following variables were coded:

- *Tackles*: all first up tackles made by an individual player
- *Tackle assists*: all tackles made by an individual player where they were not the first player into that particular tackle scenario (secondary, tertiary tackler)
- *Tackles missed*: all tackles attempted by an individual player but where the player failed to effectively stop the opposing player and perform a completed tackle scenario
- *Contact carries*: all carries made by an individual player where they took the ball into contact/collision
- *Breakdown entries*: all breakdown entries by an individual player, on either the attacking (e.g. cleaner) or defending (e.g. jackler) side of the ruck
- *Contact events*: a sum of the above five variables to provide a total count of contact/sport specific actions.

4.2.5 Data Handling

All load variables (sRPE load, distance and high-speed running distance) were aggregated for all training sessions in a single day and for every individual match day to provide a single daily value for each variable. All match key performance indicator variables for first team league matches were calculated for each individual player per match. All players who played any part in a match (full match, starter, replacement) were included in the match analyses.

4.2.6 Statistical Analysis

All analyses were performed using the R software package (www.r-project.org). Mixed effect models were conducted using *lme* or *glmer* functions depending upon the distribution of the data and the subsequent transformation required (as suggested by Windt et al., 2018); to examine the effect of position (forward/back; forward as the baseline) and league of competition (Premiership/Championship; Premiership as the baseline) on all load and key performance indicator variables. When assessing training demands, sRPE load, total distance and high-speed running distance were analysed; whilst in matches the same three load variables (sRPE load, total distance and high-speed running distance), along with match duration and the six key performance indicator variables (tackles, tackle assists, tackles missed, contact carries, breakdown entries, and contact events) were assessed. Random effects for player were included in all models.

The load variables (for both matches and training) were assessed using the *lme* function, which applies linear mixed effect models (high-speed running distance analysis was undertaken using a square root transformation due to the distribution of the data). Due to the key performance indicator variables being count variables, these models were run using the *glmer* function (which applies generalised linear mixed effect models) with a Poisson (where variance $< 2x$ mean) or negative binomial distribution (where variance $> 2x$ mean) as appropriate. Match duration was also included in the key performance indicator models, given the impact of the length of time played on these variables. For all analyses, statistical significance was accepted as $p<0.05$.

4.3 Results

4.3.1 Training Demands

Training demands of Rugby Union (sRPE load, distance and high-speed running distance) are detailed in Tables 4.1 (forward vs. back) and 4.2 (Premiership vs. Championship).

Table 4.1. Training demands of Rugby Union expressed as mean (±SD), for session RPE load, total distance and high-speed running distance. Split by position; full squad, forward and back.

Load variable	Position	Training demand	Intercept	Parameter estimate	Std. error	p-value
sRPE load (AU)	Full squad	438 (±271)	428	-14.824	8.960	0.102
	Forward	442 (±276)				
	Back	431 (±264)				
Distance (m)	Full squad	3403 (±1836)	3765	704.421	68.573	<0.001
	Forward	3069 (±1578)				
	Back	3776 (±2023)				
High-speed running distance (m)	Full squad	58 (±100)	64	12.200	7.000	0.080
	Forward	50 (±110)				
	Back	67 (±88)				

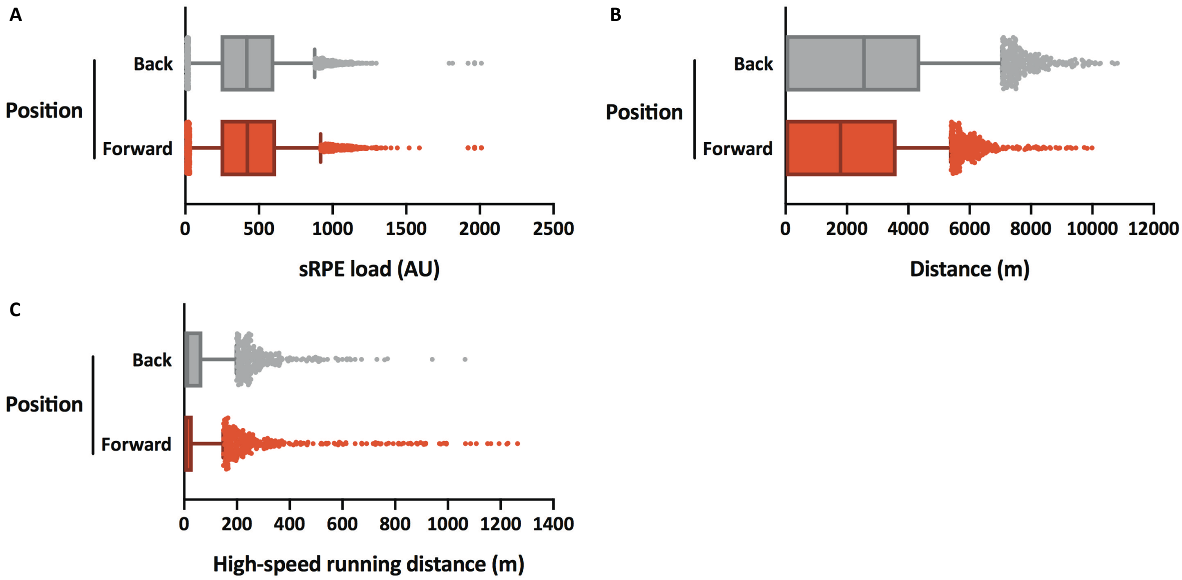


Figure 4.1. Training demands comparison between forwards and backs for combined seasons. **Fig.4.1A:** sRPE load (p = 0.051); **Fig.4.1B:** Distance (p < 0.001); **Fig.4.1C:** High-speed running distance (p = 0.080).

[Box and Whisker Plot: the box represents the interquartile range (25%-75%), with the whikser presenting the 5th and 95th centiles and the dots presenting the extreme values].

When comparing forwards and backs, backs run on average 704 m further per training session compared to the forwards (p<0.001; fig. 4.1B). However, there was no difference in training demand for either for sRPE load or high-speed running distance (p>0.05) between forwards and backs.

Table 4.2. Training demands of Rugby Union expressed as mean (±SD), for session RPE load, total distance and high-speed running distance. Split by league of competition; combined, Premiership and Championship for the full squad.

Load variable	Position	Training demand	Intercept	Parameter estimate	Std. error	p-value
sRPE load (AU)	**Combined**	438 (±271)	428	15.930	5.282	0.003
	Premiership	427 (±271)				
	Championship	448 (±271)				
Distance (m)	**Combined**	3403 (±1836)	3492	-190.698	59.380	0.001
	Premiership	3517 (±1913)				
	Championship	3338 (±1788)				
High-speed running distance (m)	**Combined**	58 (±100)	59	-3.000	3.000	0.438
	Premiership	57 (±76)				
	Championship	59 (±112)				

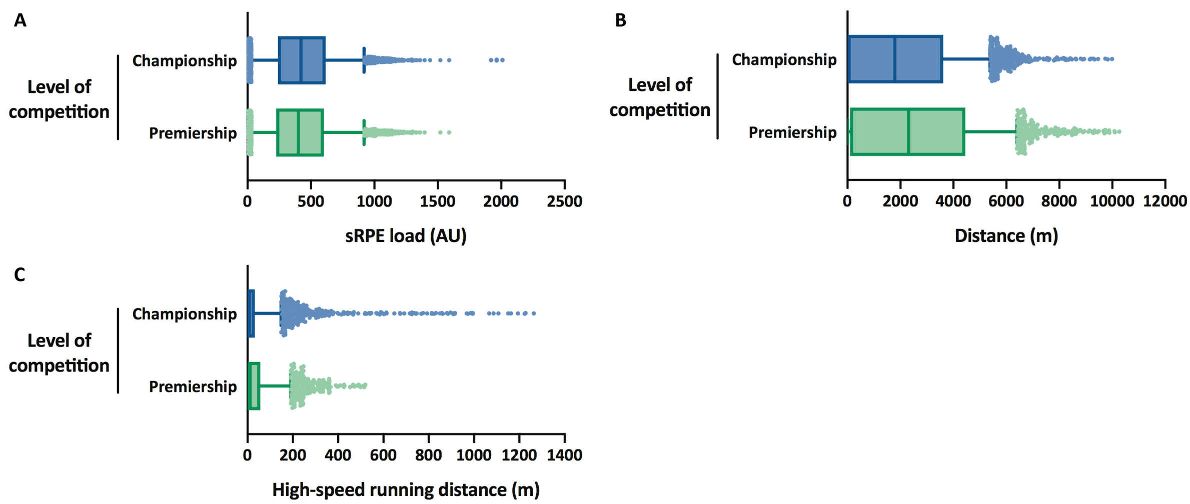


Figure 4.2. Training demands comparison between the Premiership and the Championship seasons for the full squad. **Fig.4.2A:** sRPE load (p = 0.003); **Fig.4.2B:** Distance (p = 0.001); **Fig.4.2C:** High-speed running distance (p = 0.438).

In the Premiership season the squad averaged 16 AU per session less sRPE load compared to the Championship season ($p = 0.003$; fig.4.2A), whereas the squad ran on average 191 m more distance per training session in the Premiership season compared to the Championship season ($p = 0.001$; fig.4.2B). However, there was no difference in training demands for high-speed running distance ($p>0.05$) between the Premiership and Championship seasons.

4.3.2 Match Demands

The was no difference in match duration between forwards and backs ($p = 0.281$) or between the Premiership and the Championship ($p = 0.197$).

Table 4.3. Match demands of Rugby Union and the multilevel model characteristics expressed as mean (±SD), for session RPE load, distance (m·min^{-1}) and high-speed running distance (m·min^{-1}). Split by position; full squad, forward and back.

Load variable	Position	Match demand	Intercept	Parameter estimate	Std. error	p-value
sRPE load (AU)	Full squad	670 (±312)	676	-2.541	41.924	0.952
	Forward	674 (±322)				
	Back	666 (±303)				
Distance (m·min^{-1})	Full squad	69.8 (±10.3)	66.3	7.566	1.422	<0.001
	Forward	66.3 (±8.3)				
	Back	74.3 (±10.8)				
High-speed running distance (m·min^{-1})	Full squad	1.29 (±1.14)	0.75	1.223	0.130	<0.001
	Forward	0.79 (±0.83)				
	Back	1.91 (±1.16)				

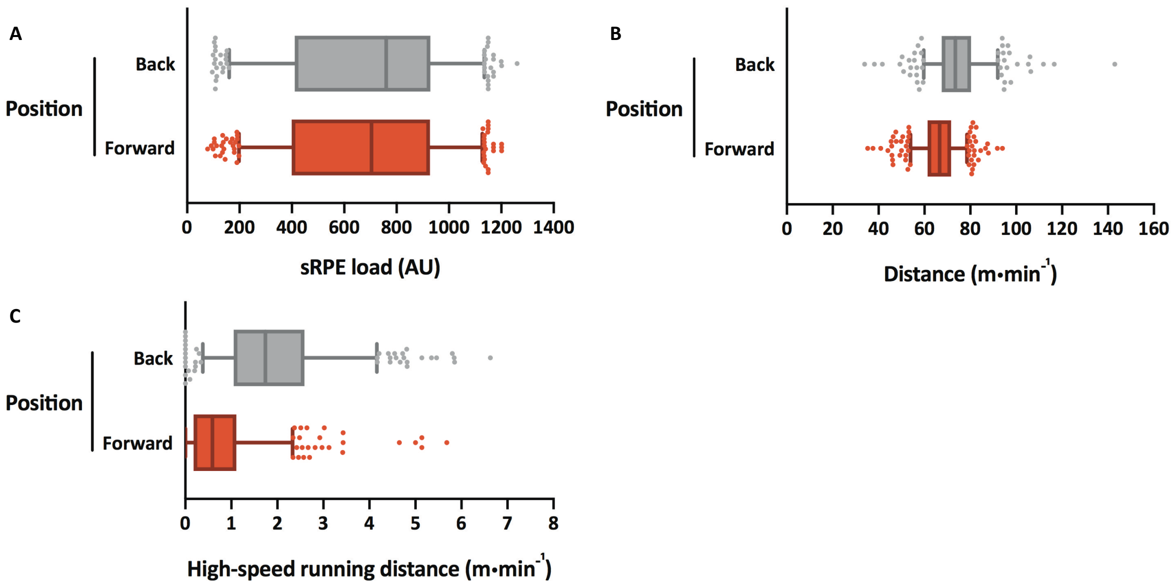


Figure 4.3. Match demands comparison between forwards and backsfor combined seasons. **Fig.4.3A:** sRPE load (p = 0.952); **Fig.4.3B:** Distance (p<0.001); **Fig.4.3C:** High-speed running distance (p<0.001).

The backs averaged 7.6 m·min^{-1} greater distance and 1.22 m·min^{-1} greater high-speed running distance than the forwards (both p<0.001; fig.4.3B and fig.4.3C). No difference was seen between forwards and backs for sRPE load (p = 0.952).

Table 4.4. Match demands of Rugby Union and the multilevel model characteristics expressed as mean (±SD), for session RPE load, distance (m·min^{-1}) and high-speed running distance (m·min^{-1}). Split by league of competition; combined, Premiership and Championship for the full squad.

Load variable	Position	Match demand	Intercept	Parameter estimate	Std. error	p-value
sRPE load (AU)	**Combined**	689 (±303)	743	-45.098	23.118	0.051
	Premiership	704 (±318)				
	Championship	673 (±287)				
Distance (m·min^{-1})	**Combined**	70.0 (±10.0)	68.7	0.435	0.712	0.541
	Premiership	69.6 (±9.6)				
	Championship	70.3 (±10.5)				
High-speed running distance (m·min^{-1})	**Combined**	1.30 (±1.14)	1.50	-0.165	0.081	0.043
	Premiership	1.40 (±1.22)				
	Championship	1.20 (±1.05)				

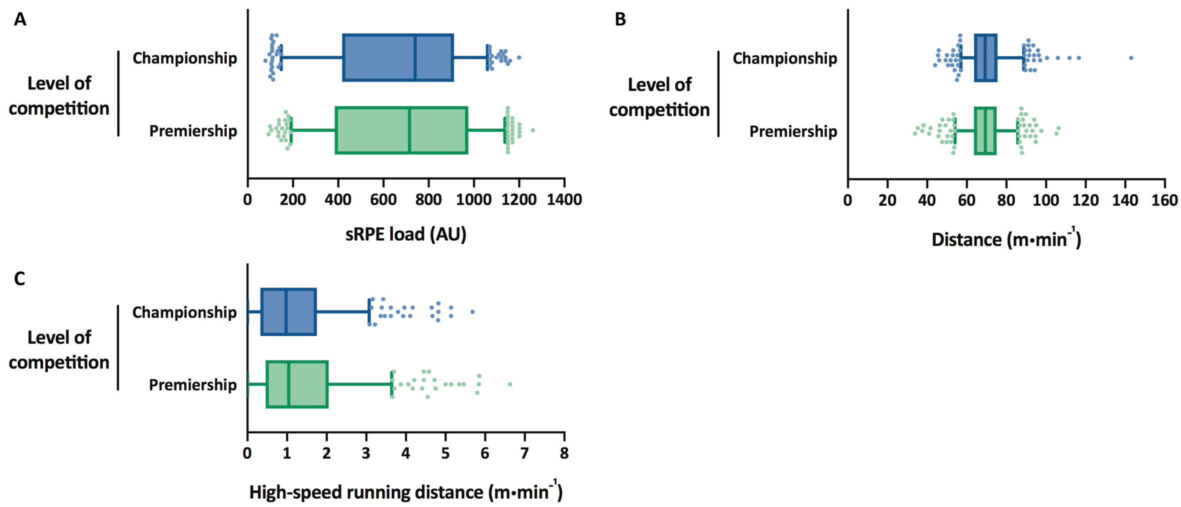


Figure 4.4. Match demands comparison between the Premiership and the Championship for the full squad. **Fig.4.4A:** sRPE load (p = 0.051); **Fig.4.4B:** Distance (p = 0.541); **Fig.4.4C:** High-speed running distance (p = 0.043).

The Premiership demand was on average 0.17 m·min^{-1} greater high-speed running distance than the Championship demand (p = 0.043; fig.4.4C). No difference was seen between the Premiership and Championship match demands for sRPE load or distance (m·min^{-1}) (p = 0.051 and p = 0.541, respectively).

4.3.3 Match Key Performance Indicator Variables Demands

Results of the mixed effect models that were conducted to examine the difference of position (forward/back) or league of competition (Premiership/Championship) on the match key performance indicator variables when controlling for match duration are presented in Tables 4.5 and 4.6 respectively.

Table 4.5. Multilevel models examining the difference between match key performance indicators for position (forward vs. back) when controlling for match duration.

Variable	Intercept	Position				Match duration				AIC	BIC	Distribution of the model
		Parameter estimate	Std. error	z-value	p-value	Parameter estimate	Std. error	z-value	p-value			
Tackles	0.658	-0.576	0.080	-7.176	<0.001	0.019	0.001	22.60	<0.001	4763	4787	Negative binomial
Tackle assists	-0.456	-1.120	0.131	-8.50	<0.001	0.019	0.002	12.20	<0.001	3095	3119	Negative binomial
Tackles missed	-1.531	0.056	0.117	0.477	0.634	0.017	0.002	10.10	<0.001	2189	2208	Poisson
Contact carries	0.134	-0.087	0.117	-0.742	0.458	0.017	0.001	20.10	<0.001	4275	4299	Negative binomial
Breakdown entries	1.285	-1.444	0.113	-12.80	<0.001	0.020	0.001	26.10	<0.001	5234	5258	Negative binomial
Contact events	2.059	-0.777	0.051	-15.40	<0.001	0.019	0.001	43.90	<0.001	6198	6222	Negative binomial

Table 4.6. Multilevel models examining the difference between match key performance indicators for league of competition (Premiership vs. Championship) when controlling for match duration.

Variable	Intercept	League of competition: Parameter estimate	Std. error	z-value	p-value	Match duration: Parameter estimate	Std. error	z-value	p-value	AIC	BIC	Distribution of the model
Tackles	1.085	-0.427	0.049	-8.973	<0.001	0.018	0.001	22.320	<0.001	4726	4751	Negative Binomial
Tackle assists	-1.153	0.181	0.094	1.917	0.055	0.018	0.002	1.151	<0.001	3141	3166	Negative Binomial
Tackles missed	-1.077	-0.300	0.088	-3.422	0.001	0.017	0.002	10.280	<0.001	2177	2197	Poisson
Contact carries	-0.090	0.127	0.050	2.563	0.010	0.018	0.001	20.270	<0.001	4269	4293	Negative Binomial
Breakdown entries	0.560	0.103	0.046	2.259	0.024	0.019	0.001	25.270	<0.001	5313	5338	Negative Binomial
Contact events	1.817	-0.041	0.027	-1.158	0.129	0.018	0.001	41.930	<0.001	6297	6322	Negative Binomial

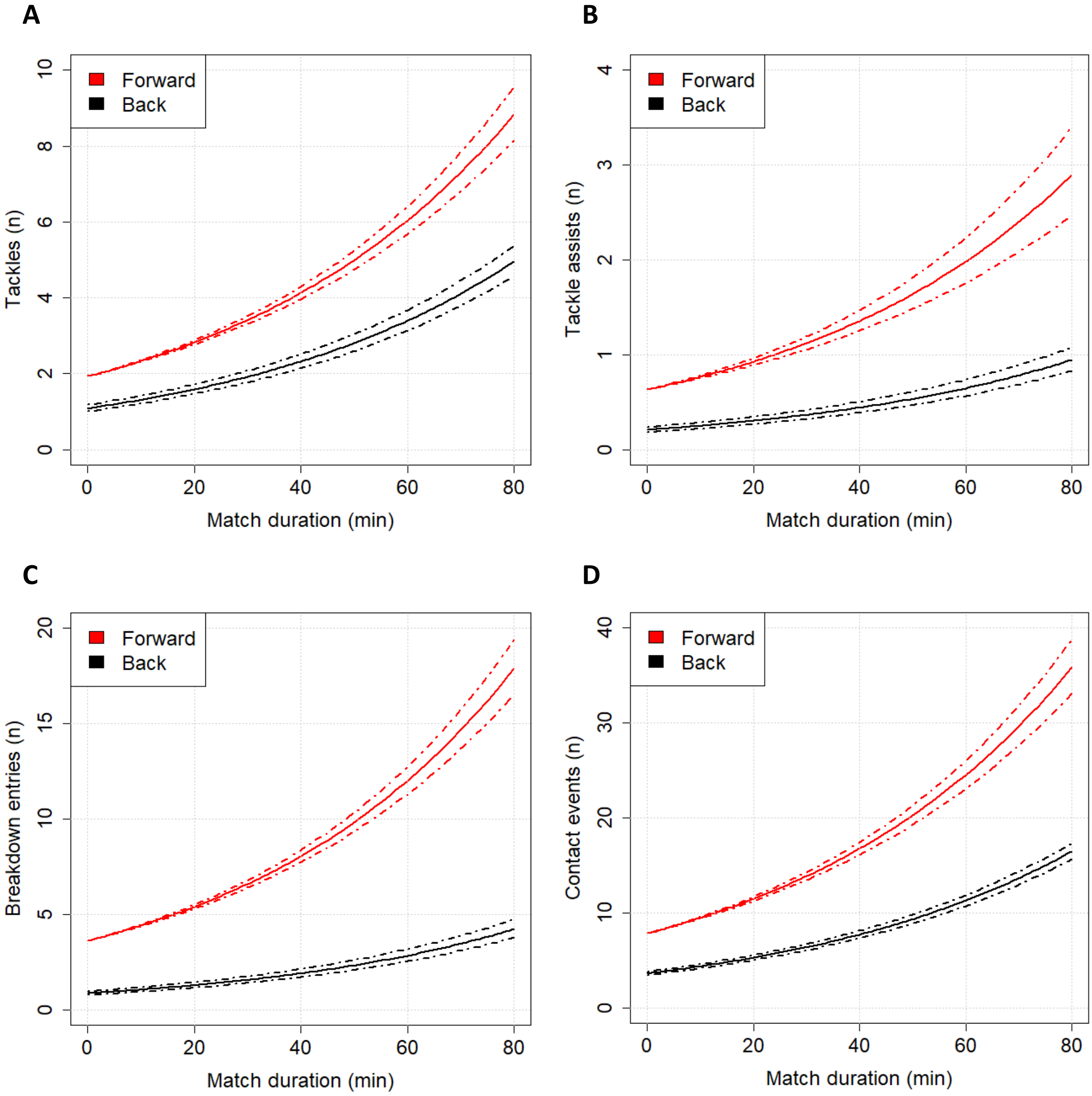


Figure 4.5. Data showing that the number of tackles was 78% greater (**Fig.4.5A**; p<0.001), tackle assists was 207% greater (**Fig.4.5B**; p<0.001), breakdown entries was 324% greater (**Fig.4.5C**; p<0.001) and contact events was 177% greater (**Fig.4.5D**; p<0.001) in forwards, compared to backs. Figures also show the effect of match duration. Data are mean ± standard error.

The number of tackles (78% greater, p<0.001), the number of tackle assists (207% greater, p<0.001), the number of breakdown entries (324% greater, p<0.001) and the number of contact events (117% greater, p<0.001) were all higher in forwards compared to backs (Table 4.5; Figure 4.5). However, the number of tackles missed (p = 0.634) and number of contact carries (p = 0.458) were not different between forwards and backs, when controlling for match duration.

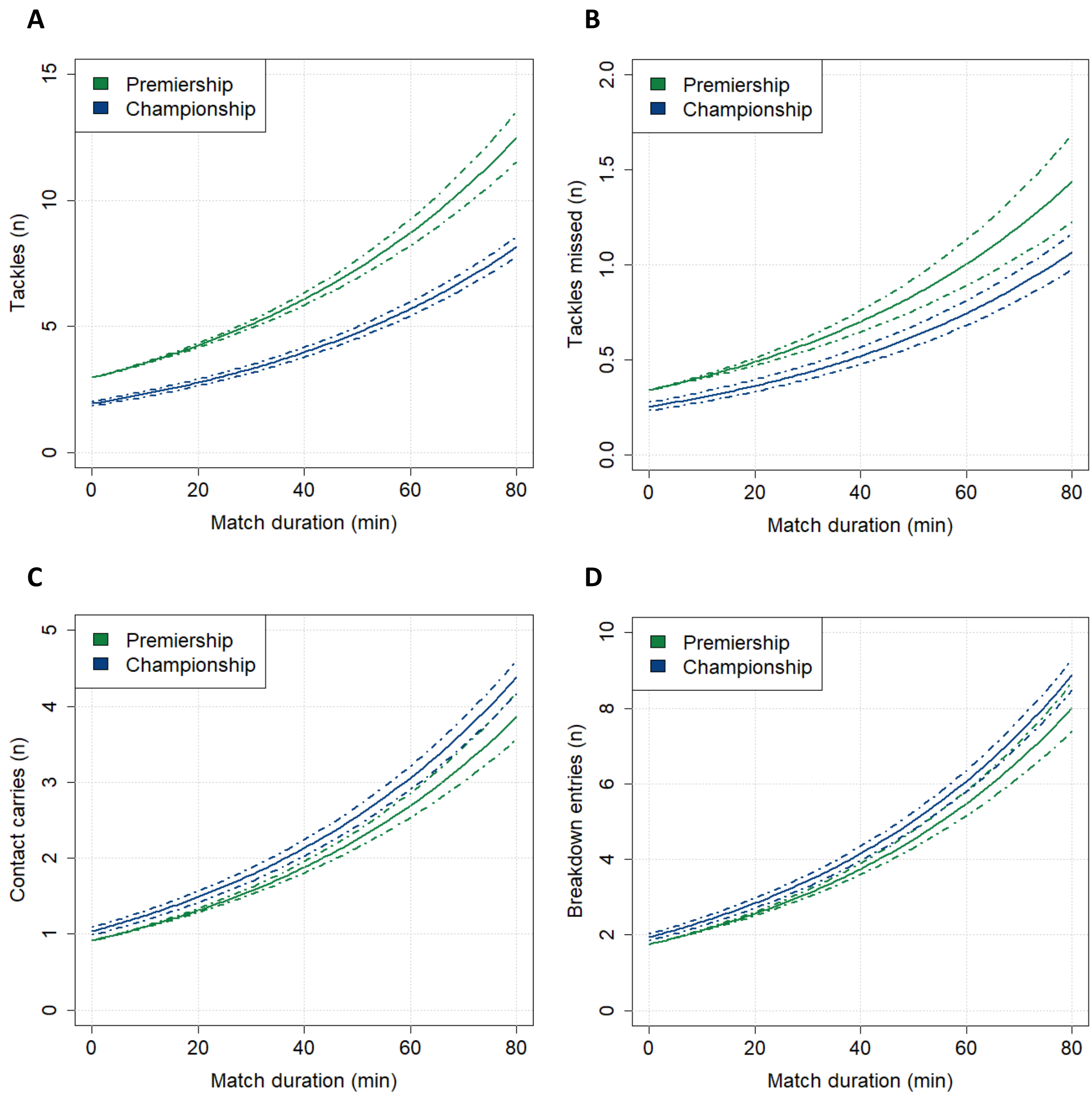


Figure 4.6. Data showing that the number of tackles was 53% greater (**Fig.4.6A**; p<0.001), tackles missed was 35% greater (**Fig.4.6B**; p = 0.001), contact carries was 12% lower (**Fig.4.6C**; p = 0.010) and breakdown entries was 10% lower (**Fig.4.6D**; p = 0.024) in the Premiership, compared to the Championship. Figures also show the effect of match duration. Data are mean ± standard error.

The number of tackles (53% greater, p<0.001) and the number of tackles missed (35% greater, p<0.001) were higher in the Premiership compared to the Championship, whereas the number of contact carries (12% less, p = 0.010) and the number of breakdown entries (10% less, p = 0.024) were lower in the Premiership compared to the Championship (Table 4.6; Figure 4.6). The number of tackle assists (p = 0.055) and the number of contact events (p =

0.129) were not different between the Premiership and Championship, when controlling for match duration.

4.3.4 Calculating Key Performance Indicator Variable Rate

The mixed effect models provided here can be used to calculate the key performance indicator variable rate (e.g. number of tackles). For example, the calculation for the number of tackles made if the position is a forward, is as follows:

Number of tackles = exp(intercept + (match duration parameter estimate x match duration))

For example, a forward playing 60 minutes, the calculation would be:

exp(0.658 + (0.019 x 60))
=exp(1.798) = 6.04 = 6 tackles

When calculating the key performance indicator variable rate for a back, the calculation requires the position effect parameter estimate:

Number of breakdown entries = exp(intercept + position effect parameter estimate + (match duration parameter estimate x match duration))

Therefore, a back playing 70 minutes, the calculation for breakdown entries would be:

exp(1.285 + -1.444 + (0.020 x 70))
=exp(1.241) = 3.46 = 3 breakdown entries

This follows the same process when calculating the Premiership or Championship demand. The Championship equation must include the league of competition parameter estimate in the same manner of calculating the backs position demand.

4.4 Discussion

The aim of the present study was to examine and identify training and match demands associated with elite level Rugby Union in England. This is the first study to comprehensively examine both training and match demands of an elite level Rugby Union club, whilst also considering both the effect of position (forward vs. back) and the league of competition the club is competing at (Premiership vs. Championship) on these variables. Furthermore, the inclusion of both subjective and objective measures of load, the inclusion of both training and match data, and the inclusion of key performance indicator variables in matches make this work both novel and insightful for researchers and practitioners alike.

The main findings of the present study were the differences in distance covered demands observed in training between forwards and backs, where backs covered on average 704 m more distance per training session than forwards. Additionally, the sRPE load demand placed on players in training was higher (on average 16 AU) in the Championship season compared to the Premiership season, whereas, the distance demand was higher in the Premiership season (on average 191 m) compared to the Championship season. The match demands between the two positional groups also elicited differences with backs covering more distance (on average 7.6 $m \cdot min^{-1}$) and more high-speed running distance (on average 1.22 $m \cdot min^{-1}$) compared to forwards. The Premiership high-speed running distance demand in matches was also greater than that of the Championship (on average by 0.17 $m \cdot min^{-1}$). The match key performance indicator demands also elicited differences between positions with forwards averaging more tackles, tackle assists, breakdown entries and contact events compared to backs. Furthermore, the comparisons between league of competition also drew differences, with the Premiership demand greater for tackles and greater number of missed tackles whereas the Premiership had fewer contact carries and fewer breakdown entries compared to the Championship.

This is the first study to directly compare training demands between forwards and backs and between two levels of elite competition. The difference in training demand observed between forwards and backs is unsurprisingly given the positional demand in matches and the requirement for sport specific preparedness the training should provide (Gabbett, 2015). As demonstrated, backs cover more total distance than forwards in training, which is also seen in match demand, this finding therefore allows practitioners to align the training to match demands. The sRPE load training demands in the Premiership season were on average 16 AU lower than that of the Championship season whereas the amount of distance covered in training was 191 m more in the Premiership season. Therefore, suggesting the training sessions in the Premiership season were of higher volume in terms of the overall distances covered per training session, but at a lower intensity due to the lower sRPE load demand. The increased focus on technical/tactical skills required in the Premiership may be a contributing factor to the training demands associated with the Premiership season.

Match demands presented in Figures 4.3 and 4.4 demonstrate the differences in position and league of competition associated with elite Rugby Union. The distance and high-speed running distance demands were higher for backs compared to forwards, therefore in agreement with the findings of previous work (Cahill et al., 2013). The findings of the present study enhance that of the aforementioned study by reporting differences in the high-speed running demand between forwards and backs, backs averaging 1.22 $m{\cdot}min^{-1}$ high-speed running distance more than the forwards across two seasons of data collection. The positional differences in the physical characteristics may provide an explanation to the difference in high-speed running distance outputs between forwards and backs. It has been shown that backs have the fastest speed times and lowest body fat percentage, therefore conducive of producing higher speed outputs and ultimately accumulate greater high-speed running distances (Smart et al., 2013). Another original feature of the current study was the comparison between the top two levels of competition in England; Premiership vs. Championship. Of the three 'load' variables (sRPE load, distance and high-speed running distance), high-speed running distance presented a difference in demand between the two leagues of competition, with players on average covering the Premiership demand 0.17 $m{\cdot}min^{-1}$ more in the Premiership when compared to the Championship. Although no study has yet sought to identify physical differences between the players of the Premiership and Championship, by virtue of the higher playing division, the players operating in the Premiership may be physically superior to that of the Championship and therefore produce higher speed / power outputs than that of their Championship counterparts.

This study was the first to directly compare the potential differences in key performance indicator variables in matches between positions (forward vs. back) and league of competition (Premiership vs. Championship). When assessing disparities between the forward and back positions the forwards made a greater number of tackles (78%), greater number of tackle assists (207%) a greater number of breakdown entries (324%) and were involved in a greater number of contact events (117%). The number of tackles missed, and number of contact carries was not different between the positional groups. These findings are in agreement with those of southern-hemisphere Super 15 matches, where it was demonstrated that forwards were involved in more impacts, tackles and rucks compared to backs, as a result of their proximity to the tackle / breakdown contest and their physiological profile being more suited to the actions associated with tackling and the breakdown, whereas the backs had higher running demands (distance and high-speed running distance (Lindsay et al., 2015; Quarrie et al., 2013). Therefore, summarising, the close quarters contact elements of Rugby Union are completed predominantly by forwards, whereas the running load demands are principally completed by backs.

When evaluating the variance in key performance indicator variable match demands between the two leagues of competition analysed in the present study, interesting differences are observed. The number of tackles were greater (53%) in the Premiership compared to the Championship along with a greater number of missed tackles (35%), whereas the number of contact carries (12% less) and number of breakdown entries (10% less) were lower in the Premiership for the club and dataset under analysis. No differences were seen for the number of tackle assists and the number of contact events between the two levels. By virtue of the fact that teams making more tackles consequently insinuates they are defending for longer periods of time, which occurred in the Premiership season and the number of contact carries (when in attacking possession) in the Championship season. This coupled with the club under investigation being relegated and promoted between these two leagues of competition provides a unique comparison (England Rugby, 2020). Therefore concluding, the defensive, tackle demand was higher in the Premiership season compared to the Championship season whereas, the attacking, ball carrying demand was higher in the Championship season compared to the Premiership.

This study provides a broad review on the demands of elite Rugby Union, subsequently ensuring that future training protocols have specificity to the match demands. The findings of the present study are based on data from a single professional club, therefore its applicability to all clubs is unknown. Furthermore, breaking down the positional demands may provide greater resolution as to specific demands (e.g. prop, hooker, second row, back row, scrum-half, fly-half, centre and back 3), however this would require a significantly larger dataset than two seasons of competition from a single club. Future work could therefore investigate multiple clubs over multiple seasons, however, achieving this will be challenging, not least due to the variation in monitoring and key performance indicator definition between clubs. Some work has been done assessing the effect of key performance indicator variables on match outcome (win, lose, draw), however the addition of load variables (such as sRPE load, distance and high-speed running distance) may provide further insight into the factors affecting match performance (Bennett et al., 2018). Finally, it is well accepted that Rugby Union has one of the highest reported incidence of match injury amongst all team sport, therefore assessing the influence of the aforementioned key performance indicator variables on match injury rates may provide further rationale behind the high match injury incidence in Rugby Union (Williams et al., 2013), this will be further explored in chapter V. Where the match key performance indicator variables will be modelled against match injury incidence to investigate whether the contact actions associated with Rugby Union match play has an influence on match injury.

4.4.1 Practical Applications in Rugby Union

The findings of the present study can be utilised within training prescription practices, especially with return to play protocols following injury. The injured players exposure to the key performance indicator aspects of match play can be determined using the equations provided in section 4.3.4, and then graded up over the return to play process in frequency and intensity to ensure adequate preparation prior to match selection. Additionally, the findings of the study can be utilised by teams making the step from the Championship to the Premiership to assist in informing the training prescription processes. Ultimately, the present study provides a detailed understanding of the demands of elite Rugby Union, that can be used both as a guideline and benchmark for training prescription processes.

4.5 Conclusions

Training demand was higher for backs, averaging a greater distance per session than forwards with no difference observed between sRPE load and high-speed running distance between positions. The match demand was higher for the backs from a 'running' perspective (greater distance and high-speed running distance demand vs. forwards) with the forwards experiencing greater key performance indicator demand (greater number of tackles, tackle assists, breakdown entries and contact events vs. backs). The distance covered in training was higher during the Premiership season whereas the sRPE load demand in training was higher during the Championship season. In matches, the high-speed running distance demand was higher in the Premiership vs. Championship. The number of tackles and number of missed tackles was greater in the Premiership with the number of contact carries and breakdown entries higher in the Championship. In summary, the running demands are higher in backs (from an absolute perspective in training and a relative perspective in matches), with the close quarter contact actions of Rugby Union more closely related to the forwards, which falls in-line with the physiological characteristics of the two positional groups. The study quantifies the positional match demands of Rugby Union which ultimately allows the specificity of subsequent training protocols.

Chapter V
Match Key Performance Indicator Variables and Injury in Elite Rugby Union

5.1 Introduction

The findings of chapter IV demonstrated how the running demands associated with both training and matches were higher for the backs position, whereas the contact actions were more closely allied to the demands of the forwards position. The purpose of chapter V is to investigate whether the match key performance indicator variables, such as the number of tackles, contact carries and breakdown entries impact the likelihood of sustaining a match injury. It has been widely accepted that Rugby Union has one of the highest reported incidences of match injury amongst all professional team sports, with some studies reporting up to 218 injuries per 1000 player match hours, compared to football where injury rates of 27.5 per 1000 player match hours across 23 top European clubs was reported (Brooks and Kemp, 2008; Ekstrand et al., 2009). It is therefore crucial that Rugby Union coaches, and performance and medical staff have a clear understanding of the circumstances under which injury rates increase during match play. In addition, it is well documented that player availability is a key determinant of success in elite Rugby Union (Williams et al., 2013). This further emphasises the need to understand the factors which may contribute to and attenuate injury incidence, to ultimately optimise team performance (Carling et al., 2015).

Research exploring injury incidence in Rugby Union has focused on exposure time (i.e. minutes played) and injury rate, across multiple levels of competition from Level 2 (equivalent to the English Championship) up to International competition (World Cup tournament) (Brooks et al, 2005a; Fuller et al., 2009). One of the first papers to extensively explore the epidemiology associated with injuries in Rugby Union monitored 12 English Premiership clubs over two seasons of competition (Brooks et al., 2005a). In total, 546 players were monitored over the duration of the study with an injury defined as preventing a player from taking a full part in training or match activity for greater than 24 hours from the day on which the injury was sustained. Results demonstrated a match injury incidence of 91.0 per 1000 match hours, with no difference observed between forwards and backs (92.0 per 1000 h vs. 91.0 per 1000 h, respectively). The most common site of injury was lower limb with contact injuries accounting for 72% of all injuries sustained and on average the clubs had 18% of their players unavailable for selection as a consequence of match injury incidence. In a similar study design, a comparable match injury incidence (96.3 per 1000 h; forwards 90.3 per 1000 h, backs 103.2 per 1000 h) was reported in over 700 players in the top 2 Levels of Southern Hemisphere Rugby Union (Fuller et al., 2009). At the slightly lower Level 2 competitive standard (the Vodacom Cup), average match injury incidence was 71.2 per 1000 h (forwards; 65.2 per 1000 h, backs; 78.0 per 1000 h), which is 78% of the incidence rate reported in the English Premiership. Again, the most common site of injury was lower limb (Fuller et al., 2009). Whilst these studies provided valuable information quantifying injury incidence and the most frequent injury site in elite Rugby Union, they were based solely on match exposure time and did not examine whether particular actions during a Rugby Union match (such as tackles and contact carries) were more likely to be associated with injury incidence.

Annual Professional Rugby Injury Surveillance Project reports are produced by the English Rugby governing body, the Rugby Football Union (RFU), detailing injury rates and the most common site of injury (England Professional Rugby Injury Surveillance Project, 2018). The most recent season presented in the report (2017-18) stated a match injury incidence of 92 per 1000 h, with a mean 85 per 1000 h over the 15-year data collection period (2002-17), therefore comparable to match injury incidence rates reported previously (Brooks et al., 2005a; Fuller et al., 2009). The most common site for match injury was head / face (concussion), with incidence reported at 17.9 per 1000 h, this was followed by posterior thigh (6.4 per 1000 h), knee (4.1 per 1000 h) and anterior thigh (4.0 per 1000 h), therefore lower limb in origin. However, the data collated as part of the Professional Rugby Injury Surveillance Project report relies on all 12 Premiership clubs reporting exposure time and injury incidence to the same exact definitions. Furthermore, no statistical analysis is undertaken as part of the report and therefore, while very valuable, the data presented is purely descriptive and does not examine what factors, if any, influence incidence rates. Therefore, research exploring sport specific actions and how they may relate to injury incidence has not been directly examined. Key performance indicator variables such as the number of tackles and number of contact carries made by an individual player, have the potential to add perspective to the factors affecting injury incidence during matches.

Therefore, the aim of this study was to examine the effect of key performance indicator variables on match injury incidence in the top two levels of competition in England (Premiership and Championship). The study followed a professional Rugby Union team that, across two seasons, played in both levels of competition and thus, allows a unique comparison between these levels of play within the same club.

5.2 Methodology

5.2.1 Study Design

The cohort of Rugby Union players examined in this study is consistent with the other chapters presented in this thesis (n = 89). Participant characteristics can be found in the general methods (Chapter III). In brief, all first-team league matches (n = 44 matches) were evaluated based on key performance indicator variables and injuries sustained therein.

5.2.2 Key Performance Indicators

For all first team league matches a host of key performance indicator variables were coded by the club's performance analyst. All variables were coded by the same performance analyst to ensure consistency between matches using performance analytics software (Sportscode Version 11, Hudl, Lincoln, Nebraska). The following variables, which best quantify the contact actions associated with Rugby Union (Fuller et al., 2007b), were coded:

- *Tackles*: all first up tackles made by an individual player
- *Tackle assists*: all tackles made by an individual player where they were not the first player into that particular tackle scenario (secondary, tertiary tackler)
- *Tackles missed*: all tackles attempted by an individual player but where the player failed to effectively stop the opposing player and perform a completed tackle scenario

- *Contact carries*: all carries made by an individual player where they took the ball into contact / collision
- *Breakdown entries*: all breakdown entries by an individual player, on either the attacking (e.g. cleaner) or defending (e.g. jackler) side of the ruck
- *Contact events*: a sum of the above five variables to provide a total count of contact / sport specific actions.

5.2.3 Injury Definitions

All injury definitions are consistent throughout the thesis and can be found in the general methods (Chapter III). In brief, all injuries sustained during match play were categorised by the club's medical staff and were defined as any physical complaint that resulted in that individual being unable to take a full part in any subsequent field- or gym-based training session or match, in line with the consensus statement defined by the International Rugby Board in 2007 (Fuller et al., 2007a). The modality, whether the injury was sustained through either contact or non-contact, and the site at which the injury occurred was also recorded, details on the exact sites can be found in the general methods (Chapter III).

5.2.4 Data Handling

All key performance indicator variables for first team league matches were calculated for each individual player per match, along with all injury data for the corresponding fixtures. All players who played any part in a match (full match, starter, replacement) were included in the analysis.

5.2.5 Statistical Analysis

The first section of the results presents descriptive data on the injury surveillance of Rugby Union matches. To assess the impact of each key performance indicator variable on injury incidence, mixed effect models were conducted using the *glmer* function in R (as suggested by Windt et al., 2018). All models were fit with a Bernoulli outcome distribution (i.e., injury or no injury) and random effects for player, season and season match number were included in all models. A further mixed effect model was run on the key performance indicator variables expressed per min of match played for each individual player per match, to account for players that did not complete the full match (replacements and injuries). For all analyses, statistical significance was accepted as $p<0.05$.

5.3 Results

5.3.1 Descriptive Data

Descriptive injury incidence data (per 1000 match h) from all matches are presented in Tables 5.1 and 5.2, for the combined, Premiership and Championship seasons (Table 5.1) and then by mode of injury occurrence (contact / non-contact; Table 5.2). Across two seasons of data collection, from 44 first-team league matches, a total of 139 match injuries occurred; with 70 match injuries in the Premiership season and 69 match injuries in the Championship season. Of the 139 match injuries, 121 (87%) were contact injuries and 18 (13%) were non-contact injuries.

Table 5.1. Injury surveillance data (injury incidence by body site) of matches in Rugby Union across two seasons, in absolute numbers and expressed relative to 1000 match exposure hours. Combined or split by season (Premiership and Championship).

Site	Combined	Premiership	Championship
Number of injuries	**139**	**70**	**69**
Injuries per 1000 match hours			
All sites	137.2	135.7	138.8
Head / face	21.7	15.5	28.2
Neck / cervical spine	4.9	9.7	0.0
Sternum / ribs / upper back	3.9	1.9	6.0
Abdomen	2.0	3.9	0.0
Low back	5.9	7.8	4.0
Sacrum / pelvis	0.0	0.0	0.0
Shoulder / clavicle	14.8	17.4	12.1
Upper arm	1.0	1.9	0.0
Elbow	3.0	5.8	0.0
Forearm	1.0	1.9	0.0
Wrist	0.0	0.0	0.0
Hand / finger / thumb	2.0	0.0	4.0
Hip / groin	5.9	3.9	8.0
Anterior thigh	11.8	3.9	20.1
Posterior thigh	3.9	3.9	4.0
Knee	21.7	15.5	28.2
Lower leg / Achilles tendon	8.9	5.8	12.1
Ankle	11.8	13.6	10.1
Foot / toe	12.8	23.3	2.0

Overall injury incidence was 137.2 per 1000 h for the combined seasons, with the Premiership eliciting 135.7 per 1000 h and the Championship 138.8 per 1000 h. The most common site of injury across the two seasons was head / face and knee (21.7 per 1000 h), followed by shoulder / clavicle (14.8 per 100 h) and foot / toe (12.8 per 1000 h).

Table 5.2. Injury surveillance data (injury incidence by body site) of matches in Rugby Union across two seasons, in absolute numbers and expressed relative to 1000 match exposure hours. Split by modality of injury: contact and non-contact.

Site	Contact	Non-contact
Number of injuries	**121**	**18**
Injuries per 1000 match hours		
All sites	119.4	17.8
Head / face	21.7	0.0
Neck / cervical spine	4.9	0.0
Sternum / ribs / upper back	3.9	0.0
Abdomen	2.0	0.0
Low back	3.9	2.0
Sacrum / pelvis	0.0	0.0
Shoulder / clavicle	14.8	0.0
Upper arm	1.0	0.0
Elbow	3.0	0.0
Forearm	1.0	0.0
Wrist	0.0	0.0
Hand / finger / thumb	2.0	0.0
Hip / groin	3.9	2.0
Anterior thigh	11.8	0.0
Posterior thigh	1.0	3.0
Knee	19.7	2.0
Lower leg / Achilles tendon	3.0	5.9
Ankle	10.9	1.0
Foot / toe	10.9	2.0

As demonstrated in Table 5.2, contact injury incidence was nearly 7 times higher than the non-contact injury incidence (119.4 per 1000 h vs. 17.8 per 1000 h). The most common site of contact injury was head / face (21.7 per 1000 h), followed by knee (19.7 per 1000 h) and shoulder / clavicle (14.8 per 1000 h). The most common site of non-contact injury was lower leg / Achilles tendon (5.9 per 1000 h), followed by posterior thigh (3.0 per 1000 h) and low back, hip / groin, knee and foot / toe (2.0 per 1000 h).

5.3.2 Key Performance Indicator Variables

There was no difference in match injury incidence between forwards and backs ($p = 0.558$), thus, position was not included in any subsequent models.

Results of the mixed effect models that were conducted to examine the effect of the key performance indicator variables on injury incidence are presented in Table 5.3. There was no effect of any of the key performance indicator variables on injury incidence (all $p>0.05$; Table 5.3).

Table 5.3. Multilevel models examining the relationship between key performance indicator variables and match injury.

Variable	Intercept	Parameter estimate	Std. error	z-value	p-value	AIC	BIC
Tackles	-2.086	0.006	0.023	0.242	0.809	788	813
Tackle assists	-2.125	0.040	0.046	0.875	0.381	787	812
Tackles missed	-2.147	0.122	0.098	1.239	0.215	787	811
Contact carries	-2.008	-0.012	0.030	-0.386	0.700	788	812
Breakdown entries	-1.953	-0.012	0.015	-0.800	0.424	788	812
Contact events	-2.019	-0.002	0.008	-0.222	0.824	788	813

In addition, the models were also run with the key performance indicator variables calculated per minute of match time (Table 5.4). There was no statistically significant effect of any of the key performance indicator variables in injury incidence in these models (all p>0.05; Table 5.4).

Table 5.4. Multilevel models examining the relationship between key performance indicator variables per minute and match injury.

Variable	Intercept	Parameter estimate	Std. error	z-value	p-value	AIC	BIC
Tackles per min	-2.047	-0.105	1.522	-0.069	0.945	788	813
Tackle assists per min	-2.090	1.019	1.802	0.565	0.572	788	812
Tackles missed per min	-2.110	0.388	3.142	1.234	0.217	787	811
Contact carries per min	-1.999	-0.824	1.902	-0.433	0.665	788	813
Breakdown entries per min	-2.021	-0.230	0.847	-0.271	0.786	788	813
Contact events per min	-2.140	0.220	0.548	0.401	0.688	788	813

5.4 Discussion

The aim of the present study was to identify the effect of key performance indicator variables (such as the number of tackles made, tackle assists and contact carries) on match injury incidence in elite Rugby Union players. The main finding of the present study is that the key performance indicator variables (tackles, tackle assists, tackles missed, contact carries, breakdown entries and contact events) did not influence match injury incidence. This is the first study to comprehensively examine the effect of these key performance indicator variables in matches on match injury incidence and the findings suggest that monitoring these variables is not recommended or necessary when considering match injury incidence.

A novel aspect of the study was the consideration of whether match key performance indicator variables influenced injury incidence in elite Rugby Union players. The findings suggest that none of the key performance indicator variables, expressed either in absolute of relative to the match duration of each individual player, demonstrated a relationship with match injury incidence. Previous work has hypothesised that the contact / collision events involved in the sport would have an effect on injury incidence (Brooks et al., 2005a). However, the findings of this study suggest no relationship between the key performance indicator variables (i.e. contact actions such as tackles made, contact carries, breakdown entries) and match injury incidence. This may be because every aspect of Rugby Union requires physical exertion and contact actions; such as tackles, ball carrying, scrummaging and mauling. Therefore, key performance indicator variables not explaining the variance in injury incidence may be in part due to the contact nature of Rugby Union. This means that all players experience contact actions during a match and, thus, it is the exposure to these contact actions, rather than the number of contact actions *per se*, that contributes to the high injury incidence seen in Rugby Union (Fuller et al., 2007b).

A potential alternative explanation of the findings is that a more important determinant of injury incidence in Rugby Union is the accumulation of global 'load' (i.e. the amount of exertion that a player applies during match play and/or training). Consequently, additional factors which could also be considered when assessing match injury incidence is the subjective and objective load placed on the players during match play. Load variables such as session rating of perceived exertion (sRPE) and global positioning system (GPS) variables, such as distance and high-speed running distance, may assist in explaining the means behind injury incidence in Rugby Union (further explored in chapter VII).

The present study reports an injury rate of 137.2 injuries per 1000 match exposure hours, which was higher than that presented in in previous studies examining match injury rates in English Premiership Rugby, where an incidence of 91.0 per 1000 h was reported (Brooks et al., 2005a). Furthermore, this injury rate is almost five times higher than the injury incidence reported in football, demonstrating the stark difference between the team sports (27.5 per 1000 match h; Ekstrand et al., 2009). This apparent rise in injury incidence compared to previous studies in Rugby Union may have occurred for multiple reasons. The collation of data from multiple clubs in the study of Brooks and colleagues (2005), coupled with the potential differences in reporting protocols of injury incidence rates, may explain the disparity. Furthermore, the 15-year gap between studies and the increase in physical characteristics of players and therefore intensity of collisions may have led to an increase in injury incidence over time in elite Rugby Union (Hill et al., 2018).

The most common site of injury in the present study was the head / face and knee (21.7 per 1000 h) and when comparing the findings of this study and that of previous work, a large increase in head/face injuries is seen (Brooks et al., 2005a). The detection and subsequent diagnosis of head injury has gained significant traction in recent years following the development of the head injury assessment tool, which is used at all professional matches, due to the adverse side effects observed when players sustain concussions (Kemp et al., 2008; Fraas et al., 2013; Tucker et al., 2017). The incidence of knee injury in the present study (21.7 per 1000 h) was higher than that reported in the annual Professional Rugby Injury Surveillance Project, where a knee injury incidence of 4.1 per 1000 h is reported. More generally, high lower limb injury incidence has been associated with the type of playing surface (grass vs. artificial turf) and the increased traction between footwear and pitch surface as a proposed mechanism (Thomson et al., 2015). Therefore, the increase in artificial playing surfaces in the professional game, both fully synthetic and hybrid (some artificial content) has increased exponentially in recent years and may explain the increase in lower body injury incidence, further explored in chapter VI (Drakos et al., 2013).

Unsurprisingly, contact injuries produced higher match injury incidence compared to non-contact injuries (119.4 per 1000 h vs. 17.8 per 1000 h, respectively), as shown in Table 5.2. Despite the overall non-contact injury rate being low in comparison to the contact injury rate (17.8 per 1000 h vs. 119.4 per 1000 h), the sites at which the non-contact injuries occurred was almost exclusively the lower body (hip / groin: 2.0 per 1000 h; posterior thigh: 3.0 per 1000 h; knee: 2.0 per 1000 h; lower leg / Achilles tendon: 5.9 per 1000 h; ankle: 1.0 per 1000 h; foot / toe: 2.0 per 1000 h). The relationships between load and non-contact lower body soft tissue injury has been demonstrated in Rugby League, therefore the inclusion of load variables (sRPE load and GPS data) may provide further understanding of the match injury incidence in Rugby Union (Gabbett and Ullah, 2012). Moreover, the inclusion of training data over more longitudinal timeframes, as opposed to single days in isolation, may further assist in the injury incidence exploration (Rogalski et al., 2013). The relationship between accumulated training and match load and injury incidence is further explored in chapter VII.

Whilst the present study is novel in its consideration of the key performance indicators affecting match injury incidence, a limitation of the current study could be the lack of statistical power within the dataset. The present study was a prospective cohort study of a single Rugby Union club over two seasons of competition. Therefore, the applicability to the findings of all clubs is unknown. Future research could address this limitation by assessing key performance indicators from multiple clubs over numerous seasons. However, achieving this will be challenging, not least due to the variations in monitoring and key performance indicator / injury definitions between clubs.

5.5 Conclusions

The main finding of the present study was that there was no effect of key performance indicator variables (such as tackles, contact carries and breakdown entries) on match injury incidence, when expressed in either absolute number or relative terms. Therefore, the monitoring of key performance indicator variables to assess the likelihood of match injury incidence would appear to have limited practical utility. The overall match injury incidence rate across the two seasons of investigation was 137.2 per 1000 match exposure hours, with contact injuries eliciting much higher incidence than non-contact injuries (119.4 per 1000 h vs. 17.8 per 1000 h, respectively). The head / face and knee eliciting the highest single site injury incidence (21.7 per 1000 h).

Chapter VI
Influence of Playing Surface on Match Injuries in Elite Rugby Union Players

6.1 Introduction

The findings of chapter V and the incidence rates reported in other team sports demonstrate how the match injury incidence in elite Rugby Union is alarming. An overall match injury rate of 137.2 per 1000 h match exposure was seen, one of the highest reported injury incidence rates across professional sport. For example, this is much higher when compared to Rugby League (57.0 per 1000 h; Fitzpatrick et al., 2018), Football (27.5 per 1000 h; Ekstrand et al., 2009), and Australian Rules Football (25.7 per 1000 h; Orchard and Seward, 2002). The findings of chapter V demonstrate how the match key performance indicator variables (such as the number of tackles made) do not have an influence on match injury incidence. Therefore, there is a clear requirement for a greater understanding of other, as of yet, unexplored factors contributing to the high match injury incidence rates in elite Rugby Union.

In recent years, innovations in 'sports turf' manufacture has seen an increasing number of competitive professional team sports matches taking place on fully synthetic or hybrid (some artificial content) surfaces (Drakos et al., 2013). Synthetic playing surfaces have evolved considerably since their initial introduction in the 1960s, with the artificial turf routinely installed in professional, university and community sports fields across the world (Drakos et al., 2013). The versality and durability in varying climates make them the ideal surface for multipurpose facilities, with a number of professional Rugby Union teams ground sharing with other sports like Football. However, the health and injury ramifications of playing Rugby Union on the various playing surfaces are not fully understood.

Research exploring the potential relationships between the risk of injury on artificial turf as opposed to natural grass have offered conflicting findings across a range of sports, including Football (Ekstrand et al., 2006; Mears et al., 2018) and American Football (Taylor et al., 2012;

Hershman et al., 2012; Thomson et al., 2015). A study of 290 Footballers from 10 elite European clubs who played their matches on a combination of third generation (3G) artificial turf and natural grass pitches revealed no differences between match injury incidence on artificial turf and grass (19.6 vs. 21.5 per 1000 h, respectively; Ekstrand et al., 2006). On the other hand, a link between playing surface and perceived injury has been shown in elite Footballers, where data from 1129 players displayed that 91% of all players believed the type of surface could affect their injury risk (Mears et al., 2018). Elevated soreness and pain were both perceived on synthetic turf, with surface type, surface properties and age all potential risk factors identified by the players. Additionally, a 10-season, study of National Football League (NFL) American Footballers, reported differences in lower limb injury incidence for matches played on either grass or synthetic artificial surfaces (Hershman et al., 2012). In total 5360 matches were analysed, and results showed differences in anterior cruciate ligament sprains (67% higher) and ankle eversion injuries (31% higher) on the synthetic surface compared grass surface.

An increasing number of competitive Rugby Union matches are taking place on fully synthetic or hybrid (some artificial content) surfaces. The data accumulated by the Injury Surveillance Project over the past five seasons has examined match injury incidence on grass compared to synthetic turf (excluding the hybrid pitches, which are becoming increasingly common). Descriptive data demonstrate very little difference in injury incidence between the two different types of surface (grass: 81 per 1000 h; synthetic: 77 per 1000 h; England Professional Rugby Injury Surveillance Project, 2018). However, no statistical examination was undertaken. Two further studies have explored the relationship between synthetic and grass playing surfaces in terms of injury risk (Williams et al., 2016; Ranson et al., 2018). Ranson and colleagues (2018) did find that the incidence of foot injury was greater on artificial surfaces (artificial: 3.6 per 1000 h vs. grass: 0.9 per 1000 h), which is consistent with the findings of increased likelihood of lower limb injury in American Footballers on artificial turf (Hershman et al., 2012). An increase in traction on artificial surfaces was suggested as a potential mechanism which could explain the increased incidence of lower limb injury on synthetic playing surfaces (Thomson et al., 2015).

Alongside the fully synthetic playing surfaces that have been introduced into the professional game over the past few years, hybrid pitches (natural grass combined with approximately 3% artificial fibres) have also become more common. However, the hybrid surface has been excluded from the studies exploring injury incidence in Rugby Union (Williams et al., 2016; Ranson et al., 2018). Therefore, a comparison of hybrid surfaces against natural grass and fully synthetic surfaces has not been conducted to date. Furthermore, the modality (contact vs. non-contact) and severity (i.e. number of days lost due to injury) of match injury associated with these three playing surfaces has not been considered, with previous studies just considering overall injury incidence (Ranson et al., 2018).

Therefore, the present study aimed to examine the effect of playing surface (grass, hybrid and synthetic) on match injury incidence. Furthermore, the modality (contact vs. non-contact) and severity (minor severity: ≤7 d vs. major severity: ≥8 d) of the injuries that occur on each playing surface was also explored. Based on the limited research to date in Rugby Union (Williams et al., 2016; Ranson et al., 2018), it was hypothesised that playing surfaces would have no effect on the incidence, modality or severity of match injuries in elite Rugby Union players.

6.2 Methodology

6.2.1 Study Design

The cohort of Rugby Union players examined in this study is consistent with the other chapters presented in this thesis (n = 89). Participant characteristics can be found in the general methods (Chapter III). In brief, all first team matches (n = 44) were examined across two seasons of competition. The playing surface was recorded, alongside the injury incidence, modality of injury (contact or non-contact) and severity of injury (subsequent number of days unavailable for training and/or match selection).

6.2.2. Playing Surface

The playing surface on which each match took place was recorded. Across the two seasons, the players were exposed to three different playing surfaces: fully grass laid pitches; hybrid grass pitches (also known as GrassMaster®, a playing field surface composed of natural grass combined with approximately 3% artificial fibres); and synthetic pitches (more commonly termed third generation (3G) which consists of 60 mm synthetic turf, sand and rubber infill). Table 6.1 presents the number of matches, number of player exposures and number of player exposure hours on each of the surfaces.

Table 6.1. Number of matches, player exposures and exposure hours by playing surface.

Playing surface	Matches	Player exposures	Exposure hours
Grass	18	397	411
Hybrid	22	492	509
Synthetic	4	90	94

6.2.3 Injury Definitions

All injury definitions are consistent throughout the thesis and full details can be found in the general methods (Chapter III). In brief, all injuries sustained during match play were categorised by the club's medical staff and were defined as any physical complaint that resulted in that individual being unable to take a full part in any subsequent field- or gym-based training session or match, in line with the consensus statement defined by the International Rugby Board in 2007 (Fuller et al., 2007a). The modality (contact or non-contact) and severity of injury were also recorded. Severity was based upon the number of days that a player was unavailable for training and/or matches; and was categorised as either minor (≤7 d) or major (≥8 d), based on the work of Brooks et al. (2005a). The site at which the injury occurred was also recorded in alignment with the consensus statement (Fuller et al., 2007a), and details on the exact sites can be found in the general methods (Chapter III).

6.2.4 Statistical Analysis

All players who played any part in a match (full match, starter, replacement) were included in the analyses. The first section of the results presents descriptive data on the injury incidence across the three playing surfaces (grass, hybrid, synthetic). All analyses were performed using the R software package (www.r-project.org). To assess the impact of playing surface on match injury incidence, mixed effect models were conducted using the *glmer* function (as suggested by Windt et al., 2018). All models were fit with a Bernoulli (binomial) outcome distribution and random effects for player, season and match number were included in all models. Initial models examining overall differences between the playing surfaces were conducted. Then each playing surface was applied as a factor to assess the differences in injury incidence (injury or no injury) and severity of injury (minor or major) between each of the different playing surfaces. To assess modality, separate models were run for contact (response variable: contact injury or no contact injury) and non-contact (response variable: non-contact injury or no non-contact injury) injuries. To calculate the odds ratios (OR) from models, the exponential of the parameter estimate was used, and 95% CI (1.96 * standard error) were also calculated. For all analyses, statistical significance was accepted as $p<0.05$.

6.3 Results

6.3.1 Descriptive Data

Injury incidence from the matches are presented in Table 6.2, for combined seasons by playing surface, with data presented relative to 1000 match exposure hours. Across the two seasons of data collection, from 44 first-team league matches, split across three different playing surfaces, there were a total of 139 match injuries. Of these, 34 injuries occurred in the 18 matches on a grass playing surface, 90 injuries in 22 matches on a hybrid playing surface, and 15 injuries in 4 matches on a synthetic playing surface.

Table 6.2. Injury surveillance data (injury incidence by body site) of matches in Rugby Union across two seasons, in absolute numbers and expressed relative to 1000 match exposure hours. Split by playing surface: grass, hybrid and synthetic.

Site	Grass	Hybrid	Synthetic
Number of injuries	**34**	**90**	**15**
Injuries per 1000 match hours			
All sites	82.8	176.9	160.3
Head / face	17.0	29.5	0.0
Neck / cervical spine	0.0	9.8	0.0
Sternum / ribs / upper back	2.4	5.9	0.0
Abdomen	2.4	2.0	0.0
Low back	0.0	9.8	10.7
Sacrum / pelvis	0.0	0.0	0.0
Shoulder / clavicle	4.9	21.6	21.4
Upper arm	0.0	2.0	0.0
Elbow	2.4	3.9	0.0
Forearm	0.0	0.0	10.7
Wrist	0.0	0.0	0.0
Hand / finger / thumb	0.0	3.9	0.0
Hip / groin	4.9	5.9	10.7
Anterior thigh	14.6	11.8	0.0
Posterior thigh	2.4	5.9	0.0
Knee	7.3	27.5	53.4
Lower leg / Achilles tendon	4.9	9.8	21.4
Ankle	14.6	9.8	10.7
Foot / toe	4.9	17.7	21.4

As demonstrated in Table 6.2, the overall match injury incidence was two times higher for the artificial playing surfaces (hybrid; 176.9 per 1000 h, synthetic; 160.3 per 1000 h) compared to the grass playing surface (82.8 per 1000 h). When observing each playing surface in isolation, the highest injury incidence rate was 53.4 per 1000 h for knee injuries sustained on a synthetic playing surface, which was 1.8 times higher than the next highest single site injury incidence (head / face on hybrid surface; 29.5 per 1000 h). The highest injury incidence rate on grass was 17.0 per 1000 h for head / face injury. Additionally, the incidence of knee injury was 7 times higher on synthetic playing surface compared to grass (53.4 per 1000 h vs. 7.3 per 1000 h) and 3 times higher on the hybrid surface compared to grass (27.5 per 1000 h vs. 7.3 per 1000 h).

6.3.2 Mixed Effect Models

6.3.2.1 Injury Incidence

Results of the mixed effect model to examine the difference in injury incidence between playing surfaces are presented in Table 6.3.

Table 6.3. Multilevel model examining the relationship between match injury incidence and playing surface.

Variable	Intercept	Parameter estimate	Std. error	z-value	p-value
Playing surface	-1.391	-0.422	0.176	-2.401	0.016

As shown in Table 6.3, a difference between the three playing surfaces was seen ($p = 0.016$). Therefore, post-hoc testing was undertaken, with playing surface as a factor, to analyse the difference between the individual surfaces (Table 6.4).

Table 6.4. Multilevel models examining the relationship between match injury incidence and for each playing surface versus alternative surfaces.

Playing surface	Parameter estimate	Std. error	z-value	p-value	Odds ratio	95% CI	
						Lower	Upper
Hybrid vs. grass	0.948	0.228	4.163	<0.001	2.58	1.65	4.03
Synthetic vs. grass	0.769	0.360	2.136	0.033	2.16	1.07	4.37
Hybrid vs. synthetic	0.179	0.332	0.538	0.590	1.20	0.62	2.29

Note: The second pitch acts as the baseline in each comparison (e.g. hybrid vs. grass represents the OR of getting injured on a hybrid playing surface compared to a grass playing surface; i.e. grass OR = 1.00). In each comparison, the inverse of the OR can be used to calculate the OR for injury on the opposing surface; e.g. OR for sustaining an injury on grass compared to a hybrid pitch is 0.39 (i.e. 1 / 2.58 = 0.39).

The odds of getting injured was more than twice as great on the hybrid playing surface (OR = 2.58, $p<0.001$) and synthetic playing surface (OR = 2.16, $p = 0.033$) compared to grass. However, there was no difference between the hybrid and synthetic surfaces ($p = 0.590$).

The percentage of injury occurrence versus no injury occurrence is presented in Figure 6.1. When players were exposed to the grass playing surface an injury occurred 9% of the time, whereas an injury occurred on 18% of the player exposures to the hybrid playing surface and on 17% of the player exposures to the synthetic playing surface.

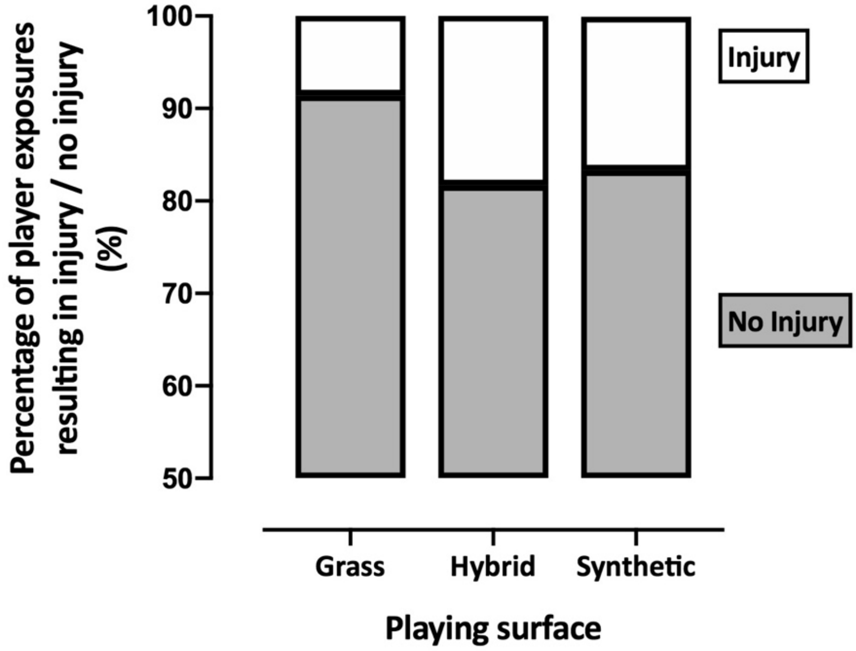


Figure 6.1. Match injury incidence percentage (injury or no injury) by playing surface (grass, hybrid and synthetic).

6.3.2.2 Modality of Injuries

The differences in the incidence of contact and non-contact injuries by playing surface are presented in Table 6.5.

Table 6.5. Multilevel models examining the relationship between contact and non-contact match injury incidence for each playing surface versus alternative surfaces.

Contact injuries							
Playing surface	Parameter estimate	Std. error	z-value	p-value	Odds ratio	95% CI Lower	95% CI Upper
Hybrid vs. grass	0.837	0.252	3.317	0.001	2.31	1.41	3.78
Synthetic vs. grass	0.783	0.398	1.967	0.049	2.19	1.00	4.77
Hybrid vs. synthetic	0.054	0.370	0.146	0.884	1.06	0.51	2.18
Non-contact injuries							
Playing surface	Parameter estimate	Std. error	z-value	p-value	Odds ratio	95% CI Lower	95% CI Upper
Hybrid vs. grass	1.431	0.653	2.193	0.028	4.18	1.16	15.04
Synthetic vs. grass	0.458	1.181	0.388	0.698	1.58	0.16	16.00
Hybrid vs. synthetic	0.983	1.064	0.923	0.356	2.67	0.33	21.51

Note: The second pitch acts as the baseline in each comparison (e.g. hybrid vs. grass represents the OR of sustaining a contact or non-contact injury on a hybrid playing surface compared to a grass playing surface; i.e. grass OR = 1.00). In each comparison, the inverse of the OR can be used to calculate the OR for contact or non-contact injury on the opposing surface; e.g. the OR for sustaining a contact injury on grass compared to a hybrid pitch is 0.43 (i.e. 1 / 2.31 = 0.43).

The odds of sustaining a contact injury on the hybrid playing surface (OR = 2.31, p = 0.001) and synthetic playing surface (OR = 2.19, p = 0.049) were two times greater than on grass. In terms of non-contact injury, the only relationship observed was a four-fold increase on the hybrid playing surface (OR = 4.18, p = 0.028) when compared to the likelihood of sustaining a non-contact injury on grass.

6.3.2.3 Severity of Injuries

The likelihood of sustaining a major (≥8 d lost) injury over a minor (≤7 d lost) injury was not different between the playing surfaces (all p>0.05; Table 6.6). Therefore, despite seeing an increase in the overall, contact and non-contact injury incidence on the hybrid playing surface, no difference in the severity of the subsequent injuries was seen.

Table 6.6. Post-hoc analysis characteristics for the likelihood of sustaining a major severity injury over a minor severity injury for each playing surface versus alternative surfaces.

Playing surface	Parameter estimate	Std. error	z-value	p-value	Odds ratio	95% CI	
						Lower	Upper
Hybrid vs. grass	0.183	0.564	0.324	0.746	1.20	0.40	3.63
Synthetic vs. grass	0.158	0.903	0.175	0.861	1.17	0.20	6.87
Synthetic vs. hybrid	0.341	0.845	0.403	0.687	1.41	0.27	7.37

Note: The second pitch acts as the baseline in each comparison (e.g. hybrid vs. grass represents the OR of sustaining a major severity injury on a hybrid playing surface compared to a grass playing surface; i.e. grass OR = 1.00). In each comparison, the inverse of the OR can be used to calculate the OR of sustaining a major severity injury on the opposing surface; e.g. the OR for sustaining a major severity injury on grass compared to a hybrid pitch is 0.83 (i.e. 1 / 1.20 = 0.83).

6.4 Discussion

The aim of the present study was to examine the differences in match injury incidence, modality and severity between the three common playing surfaces in elite Rugby Union and test the hypothesis that no difference in incidence, modality and severity of match injury would be seen between the playing surfaces. The main findings of the present study were that, for overall injury incidence, the two surfaces with some artificial content (hybrid and synthetic) elicited higher match injury incidence compared to grass pitches (hybrid OR = 2.58; synthetic OR = 2.16). The modality of injury occurrence was also affected by the playing surface, with the odds of sustaining a contact injury on a pitch with artificial content more than double that of a natural grass surface (hybrid: OR = 2.31; synthetic: OR = 2.19). Furthermore, non-contact injury incidence was four times greater on the hybrid playing surface compared to natural grass (OR = 4.18). However, there was no effect of playing surface on the severity of the injuries that occurred.

This study is the first to assess the differences in injury incidence, modality and severity between the three most common playing surfaces that players encounter in elite Rugby Union. Therefore, this study is novel and provides insight for the professional Rugby Union boards and has practical significance in an applied setting. The findings of the present study suggest that any playing surface that contains some element of artificial material (hybrid or synthetic) resulted in approximately double the match injury incidence. This is contrary to previous work in Rugby Union exploring playing surface and match injury (Williams et al., 2016; Ranson et al., 2018), which found no differences. This could be explained by the inclusion of the hybrid playing surface in the current study (which elicited the highest injury incidence of 176.9 per 1000 h), whilst previous studies compared only grass and synthetic surfaces. However, it should also be noted that the post-hoc analysis revealed more than double the odds of injury incidence for both the hybrid and synthetic surfaces compared to grass (OR = 2.58 and 2.16, respectively). This is in contrast to the previous studies reporting no difference between grass and synthetic surfaces (Williams et al., 2016; Ranson et al., 2018). However, the possibility that synthetic surfaces may increase the risk of injury incidence is of potentially great interest to applied practitioners.

A further novel aspect of this study was that it considered the modality of injury and the influence of different playing surfaces. The contact injury rate on artificial surfaces (hybrid and synthetic) was also double that of the grass playing surface. It has been hypothesised that the momentum kinetics involved with the contact events in Rugby Union and the subsequent increase in traction and momentum as a result of the artificial surface may explain the increase observed in contact injuries on artificial surfaces (Hendricks et al., 2014; Thomson et al., 2015). The present study therefore provides important novel evidence of an increased incidence of contact injuries on artificial (both hybrid and synthetic) playing surfaces. The non-contact injury incidence was similar between the grass and synthetic playing surfaces. However, the odds of sustaining a non-contact injury on the hybrid playing surface was over four times that of grass, again suggesting that even a small proportion of artificial content is associated with a rise in the incidence of this type of injury.

Additionally, the present study is the first to document that, despite differences in injury incidence, the severity of the resulting injuries was not different between grass, hybrid and synthetic playing surfaces (all p>0.05; Table 6.6). With no differences seen in the severity of injury, it suggests a similar 'seriousness' of injuries on all playing surfaces. However, the injuries occur more frequently on the hybrid and synthetic surfaces compared to grass, as demonstrated through the higher incidence rates in Table 6.2. This is in agreement with the findings of the two previous studies in Rugby Union where no difference in the severity of match injury was seen between synthetic and grass pitches (Williams et al., 2016; Ranson et al., 2018).

The highest single site injury incidence for any playing surface in this study was knee injuries sustained on the synthetic surface (53.4 per 1000 h, Table 6.2), more than 1.8 times higher than the next highest single site of injury incidence. This is in agreement with the Professional Rugby Injury Surveillance Project and a study of American footballers (NFL) (England Professional Rugby Injury Surveillance Project, 2018; Hershman et al., 2012), whereby there was an increase in lower limb injury incidence on the synthetic playing surface. It has been suggested that may be due to an increase in rotational traction on synthetic surfaces, a common cause of knee injury (England Professional Rugby Injury Surveillance Project, 2018; Hershman et al., 2012; Thomson et al., 2015). The present study would support these suggestions but did not have adequate power to statistically consider separately the site of injury between playing surfaces; a potential avenue for further investigation.

This study provides a comprehensive review on the differences in injury incidence, modality and severity between the common playing surfaces (grass, hybrid and synthetic) in elite Rugby Union; providing practitioners (Rugby coaches and performance and medical staff) with an awareness of the potential implications when playing matches on different surfaces. A potential limitation of the present study is that results are based on data from a single professional club over two seasons of competition (n = 44 matches), therefore the applicability of the findings to all clubs is unknown. Future research could consider sampling numerous clubs over multiple seasons on the three playing surfaces. Despite the limited sample size in the current study, marked differences in the injury rates between playing surfaces were observed. The difference in both contact and non-contact injury, and more specifically knee injuries sustained on synthetic pitches warrants further investigation in larger cohorts. The specific interactions between footwear and the playing surface, traction properties and momentum kinetics are avenues which could be explored and may provide mechanistic insight regarding the underlying causes of incidence and modality of injury. Furthermore, the inclusion of training data into future data sets (playing surface and injury incidence) may provide additional findings of great importance to support staff at elite Rugby Union clubs.

6.4.1 Practical Applications in Rugby Union

Previous research has suggested that the playing surface on which Rugby Union match play took place did not alter the likelihood of sustaining match injury (Williams et al., 2016; Ranson et al., 2018). However, the findings of this study suggest that a playing surface containing some artificial content (hybrid or synthetic) increases the odds of sustaining a match injury. The practical utility of this finding is that Rugby Union management staff (e.g. coaches and medical staff) have the knowledge that when competing on a playing surface containing some artificial content an increase in the likelihood of sustaining an injury is seen. Furthermore, whilst the present addressed only the relationship between playing surface and match injury, it can be hypothesised that a similar relationship would be observed for the likelihood of injury in training sessions taking place on either hybrid or synthetic surfaces. Therefore, to minimise the likelihood of training injury incidence, training sessions on hybrid and synthetic surfaces in preparation for matches should be kept to a minimum and only used when absolutely necessary.

6.5 Conclusions

The current study's findings suggest that the playing surface on which match play occurs, has a meaningful impact on overall, contact and non-contact injury incidence. Specifically, a pitch with any artificial content (hybrid or synthetic) approximately doubles the odds of sustaining an injury compared to playing on natural grass. The odds of sustaining a contact injury increased two-fold on the hybrid and synthetic surfaces compared to grass; whilst there was a four-fold increase in the odds of a non-contact injury occurring on the hybrid playing surface compared to natural grass. These findings suggest that even a small percentage (3%) of artificial content within the playing surface can have a substantial impact on match injury incidence; and thus, squad availability and performance. The findings of this study provide practitioners with the understanding that the odds of overall injury (including contact and non-contact injuries) are increased on a surface containing even a small percentage of artificial content. Therefore, the ‘risk’ associated with playing matches on artificial pitches is an important factor that is vital for applied practitioners to consider and be aware of.

Chapter VII
Match and Training Load Exposure and Time-Loss Incidence in Elite Rugby Union Players

7.1 Introduction

The findings of chapter VI demonstrated how pitch type can influence in incidence of match injury, furthermore the findings of chapter IV and V reported the match and training demands associated with Rugby Union across the Premiership and Championship and between positions (forwards and backs). An overall match injury rate of 137.2 per 1000 h match exposure conveyed in chapter V, coupled with the reported incidence of 3.0 injuries per 1000 h training exposure, Rugby Union has one of the highest reported incidences of injury amongst all professional team sports (Williams et al., 2013). Furthermore, it has been demonstrated in a number of professional sports, including Soccer (Carling et al., 2015) and Rugby Union (Williams et al., 2015), that success is inversely related to injury incidence, suggesting that player availability is a key determinant of success. It is therefore crucial that Rugby Union coaches, performance and medical staff develop strategies to reduce time-loss incidence and maximise squad availability, thus enhancing the chances of team success. As stated in chapter V, the contact actions accumulated in matches did not have an influence on match injuries, however, the running demands and potential for accumulated 'load' measured through subjective and objective means may explain the influence of match and training load exposure on time-loss incidence, which has not been well explored in Rugby Union. Therefore, the aim of chapter VII was to examine the influence of match and training load exposure and time-loss incidence in elite Rugby Union players.

Time-loss incidences are typically classified as either injuries or illness, with injuries further categorised as contact and non-contact (Fuller et al., 2007a). In elite sport, the careful management of match and training load to minimise time-loss incidence, is a key role of performance, medical and coaching staff (Gabbett and Ullah, 2012; Rogalski et al., 2013; Blanch and Gabbett, 2016; Cross et al., 2016). Improper load management can negatively affect numerous physiological systems including the neuroendocrine, immunological, cardiovascular and musculoskeletal systems (Adams and Kirkby, 2001), resulting in an increased occurrence of time-loss incidence.

Research exploring the effects of match and training load on time-loss incidence rates has typically quantified load using either subjective or objective measures. Subjective measures of match and training load include ratings of perceived exertion (RPE), with the most commonly used outcome variable being session RPE load (sRPE), calculated by multiplying session RPE (Borg CR10 scale; Foster et al., 2001) by session duration (in minutes) (Gabbett, 2004; Gabbett and Domrow, 2007). Objective measures include micro technology such as global positioning systems (GPS), which provide information such as the overall distance covered by the players in a given training session or match and the speeds at which those distances are covered (Colby et al., 2014). In recent years, research has been undertaken investigating the relationship between match and training load and time-loss incidence across a variety of sports, including Australian Rules Football (Rogalski et al., 2013), Rugby League (Blanch and Gabbett, 2016; Hulin et al., 2016), Cricket (Hulin et al., 2016) and Soccer (Bowen et al., 2017). One of the first papers to examine the relationship between match and training load and injury was conducted in 46 elite Australian Rules footballers (Rogalski et al., 2013). sRPE load showed that high training loads over one week of >1750 arbitrary units (AU) (compared to a reference group of <1250 AU) resulted in an increased occurrence of injury (odds ratio (OR) = 2.44-3.38). Two week loads of >4000 AU (compared to <2000 AU) were also associated with an increased occurrence of injury (OR = 4.74), as were large changes (from one week to the next) of greater than 1250 AU (compared to a change of <250 AU; OR = 2.58). A more objective approach has also been used in Australian Rules Football, where GPS derived running loads and injury occurrence were assessed across one season of competition (Colby et al., 2014). Total distance and sprint distance were analysed as cumulative 3-week loads and results showed that total distance between 73721 m – 86662 m (compared to <73721 m) increased the occurrence of non-contact injury (OR = 5.49), as did a high sprint (greater than 75% of the individual's maximum velocity) distance (>1453 m compared to <864 m; OR = 3.67) (Colby et al., 2014). However, this objective approach to match and training load quantification has only been examined in Australian Rules football.

A number of different methods of quantifying match and training load have also been reported in the literature to date, including the acute:chronic workload ratio (ACWR) (Blanch and Gabbett, 2016) and the exponentially weighted moving average (EWMA) (Williams et al., 2017). The acute:chronic workload ratio is the ratio of average load in the past 7 d (acute) compared to the average of the past 28 d (chronic) (Blanch and Gabbett, 2016); which when applied to sRPE load data, it has led to the suggestion of a "sweet-spot" (i.e. the match and training load associated with the lowest time-loss incidence risk) of 0.8-1.3 (80-130% in the past 7 d compared to the past 28 d). It is also interesting to note that the risk of injury increases when the acute:chronic workload ratio goes above 1.5 (Blanch and Gabbett, 2016). In more recent years researchers have questioned the rolling average approach of the acute:chronic workload ratio (Williams et al., 2017; Menaspa, 2017; Lolli et al., 2017; Lolli et al., 2018; Drew and Purdam, 2016), with the suggested new approach to place greater weighting on the load completed in the acute phase (compared to the preceding days/weeks), due to the decaying nature of fitness and fatigue effects over time (Williams et al., 2017). This approach, defined as the exponentially weighted moving average, mitigates the issues described by Menaspa (2017) and Lolli et al. (2017), such as mathematical coupling, and is therefore potentially suggested as a more sensitive measure.

One of the few studies to explore the influence of in-season training loads on injury risk specifically in professional Rugby Union was undertaken by Cross et al. (2016). sRPE load was examined across four teams (n = 173 players) for the in-season period of one season of competition. Results showed that injury risk increased when one-week load was 1245 AU greater than an average week (OR=1.68) and when week-to-week changes in load exceeded 1069 AU (compared to no change, OR = 1.58). Furthermore, a likely harmful effect was seen when four-week cumulative loads >8651 AU (compared to <3684 AU; OR = 1.39). However, the study by Cross et al. (2016), did not account for the loads accumulated from matches, which is typically the player's biggest load in a week. Additionally, no objective measures were used to quantify load, therefore no external load measurement was obtained, and training load was assessed in its absolute form, with no acute:chronic workload ratio or exponentially weighted moving average quantification applied.

Therefore, the aims of this study were to examine and identify relationships between match and training load, derived through both subjective and objective measures, and time-loss incidence rates in elite Rugby Union players, across two seasons of competition. The study sought to identify the best predictor of time-loss incidence occurrence between absolute match and training load variables, the acute:chronic workload ratio and the exponentially weighted moving average quantification methods. Furthermore, it was hypothesised that due to the decaying nature of fitness and fatigue, the exponentially weighted moving average approach to match and training load quantification would better explain the variance in time-loss incidence occurrence in comparison to the acute:chronic workload ratio method. It was also hypothesised that the acute (last 7 d) period of match and training load would be the greatest predictor of time-loss incidence occurrence compared to the longer 14, 21, and 28 d timeframes.

7.2 Methodology

7.2.1 Study Design

The cohort of Rugby Union players examined in this study is consistent with the other chapters presented in this thesis (n = 89). Participant characteristics can be found in the general methods (Chapter III). In brief, the quantification of load was undertaken using three methods; the absolute match and training load (cumulative daily load), the acute:chronic workload ratio (ACWR) (Blanch and Gabbett, 2016) and exponentially weighted moving average match and training load ratio (EWMA) (Williams et al., 2017), with these calculations applied to subjective (sRPE load) and objective (GPS) data. Additional match and training load quantification was undertaken in the format of cumulative rolling sums for 7, 14, 21, and 28 d periods, again for both sRPE load and GPS data.

7.2.2 Rating of Perceived Exertion (RPE)

For every field-based training session and match, an RPE rating, using the modified Borg CR-10 RPE scale (Foster et al., 2001), was obtained within 30 min of the end of the exercise, in line with the recommendations of Kraft et al. (2014). Session RPE load (sRPE load) in arbitrary units (AU) was then calculated for each player by multiplying the given RPE by the session duration (min) (Foster et al., 2001). This was performed for all players across both seasons of data collection. The collection of RPE data was consistent across all experimental chapters and additional information on the validity and reliability of sRPE for estimating relative exercise intensity can be found in the general methods (Chapter III). The acute:chronic workload ratio and exponentially weighted moving average calculations were then applied to the RPE data, yielding two variables: ACWR sRPE load and EWMA sRPE load. In addition, cumulative 7, 14, 21, and 28 d sums were calculated.

7.2.3 Global Positioning Systems (GPS)

An objective measure of match and training load was obtained through GPS for every field-based training session and match. The assignment, validity and reliability, software and horizontal dilution of precision information of the GPS data collection can be found in the general methods (Chapter III). Total distance and high-speed running distance (set at greater than 70% of an individual player's maximum velocity) were the two objective GPS-derived variables used throughout this study. Additional information on the determination of high-speed running threshold can be found in the general methods (Chapter III). GPS data were also quantified using acute:chronic workload ratio and exponentially weighted moving average, giving rise to four further variables (ACWR distance, EWMA distance, ACWR high-speed running distance and EWMA high-speed running distance). In addition, the cumulative 7, 14, 21, and 28 d rolling sums were calculated for both distance and high-speed running distance.

7.2.4 Data Handling

The detailed quantification methods of the acute:chronic workload ratio, exponentially weighted moving average and cumulative rolling sums can be found in section 3.4 (general methods). Due to the acute:chronic workload ratio and exponentially weighted moving average variables requiring at least 28 d of match and training load data and the cumulative sums requiring 7, 14, 21, and 28 d respectively, the overall n for each variable is varied.

7.2.5 Time-Loss Incidence Definitions

All time-loss incidences sustained were categorised by the club's medical staff and were defined as any physical complaint that resulted in that individual being unable to take full part in any field- or gym-based training session or match, in line with the consensus statement defined by the International Rugby Board in 2007 (Fuller et al., 2007a). Further information on the nature of the time-loss incidence was recorded, including severity (number of days unavailable for training and/or matches), the nature of the injury (contact, non-contact or illness) and the session in which the injury occurred (training or match). Each time-loss incidence was entered into the database for the day on which it occurred, and subsequently was associated with the absolute match and training load, acute:chronic workload ratio and exponentially weighted moving average for that day.

7.2.6 Statistical Analysis

The first section of the results presents descriptive data. To assess the impact of each match and training load quantification method on time loss-incidence occurrence, mixed effect models were conducted using the *glmer* function in R (www.r-project.org) (as suggested by Windt et al., (2018)). All models were fit with a Bernoulli outcome distribution (i.e. injury or no injury) and random effects for player, season, day of the season were included in all models. To assess the effect of matches and training on time-loss incidence occurrence, this variable was included in subsequent models for that section of the results. Position (forward/back) and age were included in all models. The exponential of the parameter estimate was used to calculate the odds. Due to co-linearity between the dependent variables, it was not possible to include several variables within the same model. Thus, separate models were performed for each variable. To enable a comparison of fit between models containing different variables, all analyses were subsequently performed on a reduced dataset with an equal number of data points for all variables (n = 14937) and the Akaike information criterion (AIC) and Bayesian information criterion (BIC) were used to assess model fit. For all analyses statistical significance was accepted as $p<0.05$.

7.3 Results

7.3.1 Descriptive Data

A total of 474 time-loss incidences were reported across the two seasons of the study, 240 time-loss incidences were reported in season one and 234 time-loss incidences in season two. Table 7.1 details the total time-loss incidence, nature of the injury and the session in which the injury occurred. Across the two seasons there were a total of 31117 exposure days, with the 474 time-loss incidences resulting in a cumulative number of 9558 days lost due to injury or illness (30.7% of total days).

Table 7.1. Number, nature and severity of time-loss incidences across the two seasons, expressed both as absolute numbers and a percentage of the total time-loss incidences/total injuries/contact injuries/non-contact injuries, as appropriate.

Season	Total time-loss incidences	Contact injuries	Non-contact injuries	Illnesses
Combined	474	237 (50.0%)	165 (34.8%)	72 (15.2%)
Premiership	240	125 (52.1%)	76 (31.7%)	39 (16.2%)
Championship	234	112 (47.9%)	89 (38.0%)	33 (14.1%)
Season	**Total injuries**	**Match injuries**	**Training injuries**	
Combined	402	257 (63.9%)	145 (36.1%)	
Premiership	201	132 (65.7%)	69 (34.3%)	
Championship	201	125 (62.2%)	76 (37.8%)	
Season	**Contact injuries**	**Contact injuries in matches**	**Contact injuries in training**	
Combined	237	205 (86.5%)	32 (13.5%)	
Premiership	125	106 (84.8%)	19 (15.2%)	
Championship	112	99 (88.4%)	13 (11.6%)	
Season	**Non-contact injuries**	**Non-contact injuries in matches**	**Non-contact injuries in training**	
Combined	165	52 (31.5%)	113 (68.5%)	
Premiership	76	26 (34.2%)	50 (65.8%)	
Championship	89	26 (29.2%)	63 (70.8%)	
Season	**Exposure days**	**Days lost (severity)**	**Percentage days lost**	
Combined	31117	9558	30.7	
Premiership	15869	4736	29.8	
Championship	15248	4822	31.6	

7.3.2 Mixed Effect Models

Results of the mixed effect models that were conducted to examine the impact of each match and training load variable on time-loss incidence are presented in Table 7.2. In all models there was no significant main effect of age or interaction between age and the variable of interest (all $p>0.05$), thus age was removed from all models. Furthermore, the interaction between position (forward/back) and the variables of interest were all non-significant (all $p>0.05$), so the interactions were removed from the model. The main effects of position were however significant so were included in the analyses.

Table 7.2. Multilevel models examining the impact of the match and training load variables on time-loss incidence.

Variable	Variable effect					Position effect			Model characteristics		
	Intercept	Parameter estimate	Std. error	Odds	p-value	Parameter estimate	Odds	p-value	AIC	BIC	Number of observations
sRPE load$	-5.058	0.108	0.014	1.11	<0.001	0.280	1.32	0.043	4407	4456	23032
ACWR sRPE load^	-4.962	0.038	0.034	1.04	0.255	0.302	1.35	0.039	4042	4090	20522
EWMA sRPE load^	-5.451	0.139	0.044	1.15	0.001	0.300	1.35	0.039	4033	4081	20522
Distance$	-5.380	0.130	0.020	1.14	<0.001	0.481	1.62	0.003	3341	3388	16927
ACWR distance^	-5.534	0.088	0.033	1.09	0.008	0.425	1.53	0.013	2990	3035	14937
EWMA distance^	-5.849	0.160	0.041	1.17	<0.001	0.408	1.50	0.014	2981	3026	14937
HSR distance$	-5.131	0.019	0.006	1.02	<0.001	0.443	1.56	0.007	3364	3410	16927
ACWR HSR distance^	-5.206	0.024	0.017	1.02	0.154	0.428	1.53	0.013	2994	3040	14937
EWMA HSR distance^	-5.439	0.073	0.024	1.08	0.002	0.446	1.56	0.009	2987	3033	14937

Key. AIC: Akaike information criterion; BIC: Bayesian information criterion; ACWR: acute:chronic workload ratio; EWMA: exponentially weighted moving average; HSR: high-speed running. Odds is the exponential of the parameter estimate and represents the increase in risk in time-loss incidence by unit of measure. $the parameter estimates, standard error and odds for the absolute load variables are presented for varying increases in units for each variable: sRPE load: 100 AU; distance: 1000 m; high-speed running distance: 10 m (e.g. an increase in sRPE load of 450 AU to 550 AU, etc.). ^the parameter estimates, standard error and odds for the ratio (ACWR and EWMA) load variables are presented for 0.2-unit increases (e.g. an increase in EWMA sRPE load from 0.8 to 1.0, etc.).

7.3.2.1 Session RPE Load

Session RPE load demonstrated a significant influence on time-loss incidence ($p<0.001$, Fig.7.1A). The odds of 1.11 indicates that for each 100 unit increase in sRPE load (e.g. from 500 AU to 600 AU, etc.), there was an 11% increase in time-loss incidence. The model also indicates that the odds of a time-loss incidence occurring in forwards was 1.32 compared to backs ($p = 0.043$). ACWR sRPE load did not influence time-loss incidence occurrence ($p = 0.255$, Fig.7.1B). However, when sRPE load was quantified using the EWMA approach, there was a significant influence on time-loss incidence ($p = 0.001$; Fig.7.1C). The odds ratio of 1.15 indicates that for each 0.2-unit increase in EWMA sRPE load (e.g. from 0.8 to 1.0, 1.3 to 1.5, etc.), there was a 15% increase in time-loss incidence. The model again indicates that the odds of a time-loss incidence occurring in forwards was higher than in backs (odds = 1.35, $p = 0.039$).

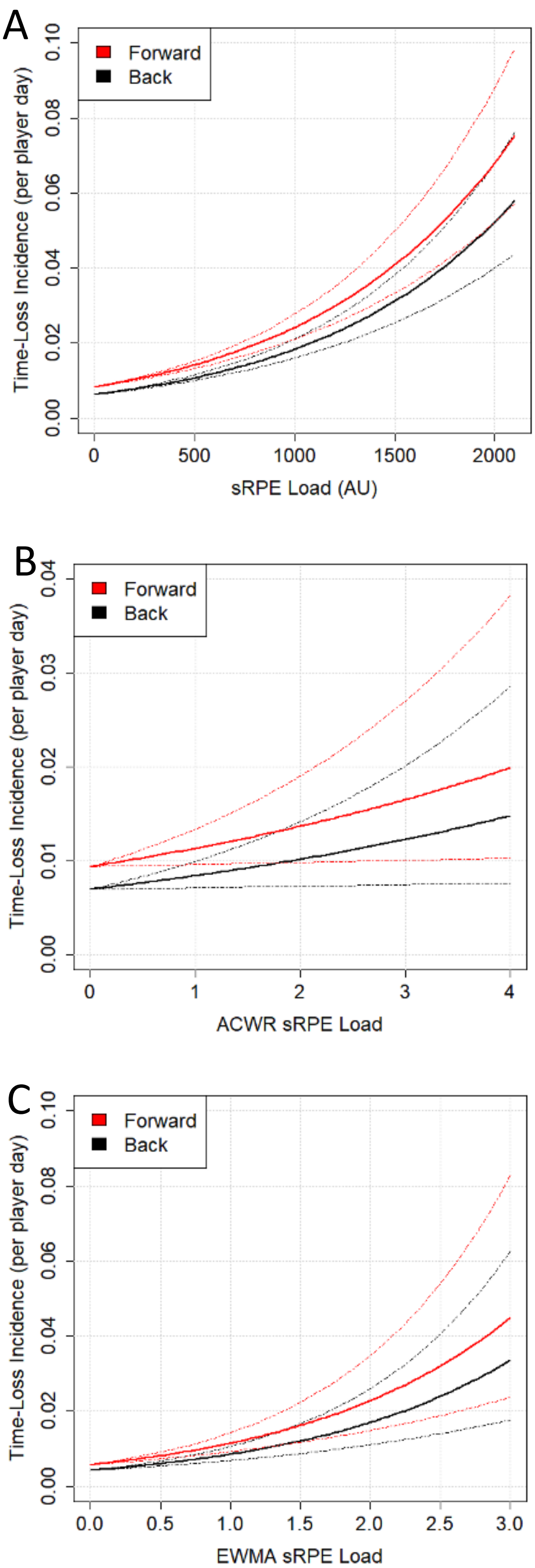
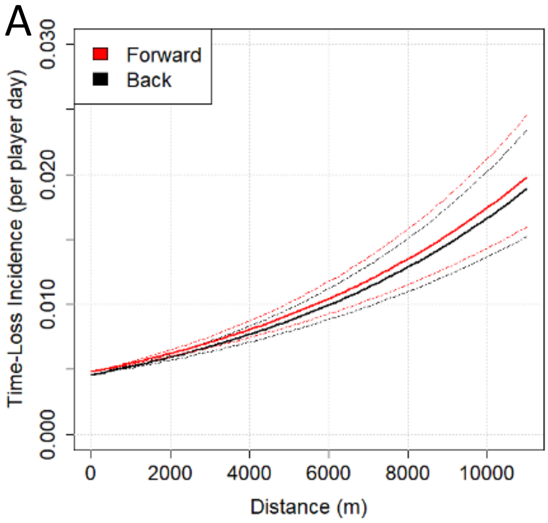
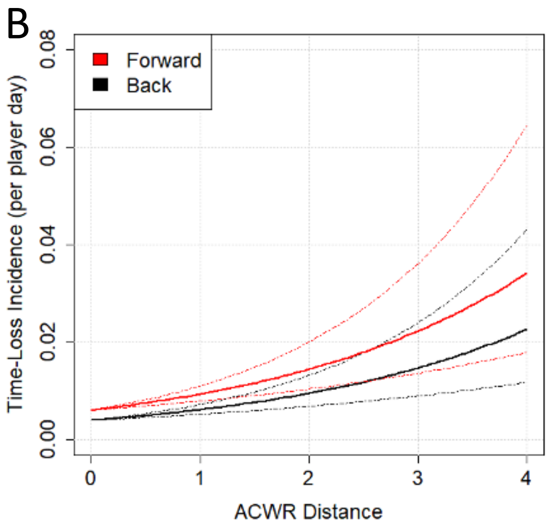


Figure 7.1. The relationship between time-loss incidence occurrence (per player day) and absolute sRPE load ($p<0.001$) **(Fig.7.1A)**, ACWR sRPE load ($p = 0.255$) **(Fig.7.1B)**, and EWMA sRPE load ($p = 0.001$) **(Fig.7.1C)**, split for forwards and backs. Data are mean ± standard error.

7.3.2.2 Distance

Distance demonstrated a significant influence on time-loss incidence ($p<0.001$, Fig.7.2A). The odds of 1.14 indicates that for each 1000 m increase in distance covered (e.g. from 1500 m to 2500 m, etc.), there was a 14% increase in time-loss incidence. The model also indicates that the odds of a time-loss incidence occurring in forwards was 1.62 compared to backs ($p = 0.003$). ACWR distance also influenced time-loss incidence ($p = 0.008$, Fig.7.2B), with the odds of 1.09 indicating a 9% increase in time-loss incidence with a 0.2-unit increase in ACWR distance (e.g. from 0.8 to 1.0, etc.). The occurrence of time-loss incidence was again greater in forwards compared to backs (odds = 1.53, $p = 0.013$). Finally, EWMA distance also demonstrated a significant influence on time-loss incidence ($p<0.001$; Fig.7.2C). The odds ratio of 1.17 indicates that for each 0.2-unit increase in EWMA distance (e.g. from 0.8 to 1.0, etc.), there was a 17% increase in time-loss incidence. The model again indicates that the odds of a time-loss incidence occurring in forwards was higher than in backs (odds = 1.50, $p = 0.014$).





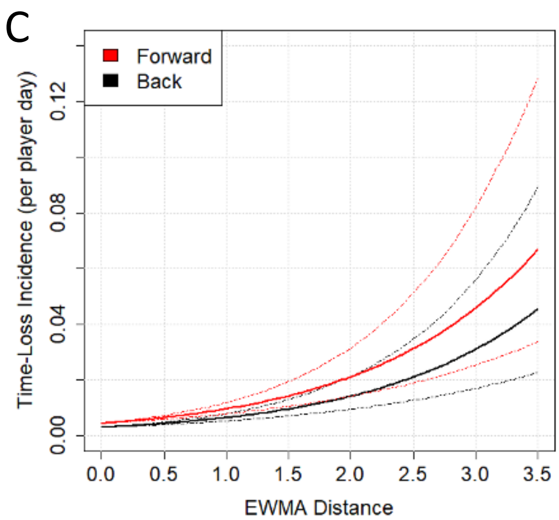


Figure 7.2. The relationship between time-loss incidence occurrence (per player day) and absolute distance ($p<0.001$) **(Fig.7.2A)**, ACWR distance ($p = 0.008$) **(Fig.7.2B)**, and EWMA distance ($p<0.001$) **(Fig.7.2C)**, split for forwards and backs. Data are mean ± standard error.

7.3.2.3 High-Speed Running Distance

High-speed running distance also demonstrated a significant influence on time-loss incidence ($p<0.001$, Fig.7.3A). The odds of 1.02 indicates that for each 10 m increase in high-speed running distance (e.g. from 80 m to 90 m, etc.), there was a 2% increase in time-loss incidence. The model also indicates that the odds of a time-loss incidence occurring in forwards was 1.56 compared to backs ($p = 0.007$). However, ACWR high-speed running distance did not influence time-loss incidence ($p = 0.154$, Fig.7.3B). Finally, EWMA high-speed running distance demonstrated a significant influence on time-loss incidence ($p = 0.002$; Fig.7.3C). The odds ratio of 1.08 indicates that for each 0.2-unit increase in EWMA high-speed running (e.g. from 0.8 to 1.0, etc.), there was an 8% increase in time-loss incidence. The model again indicates that the odds of a time-loss incidence occurring in forwards was higher than in backs (odds = 1.56, $p = 0.009$).

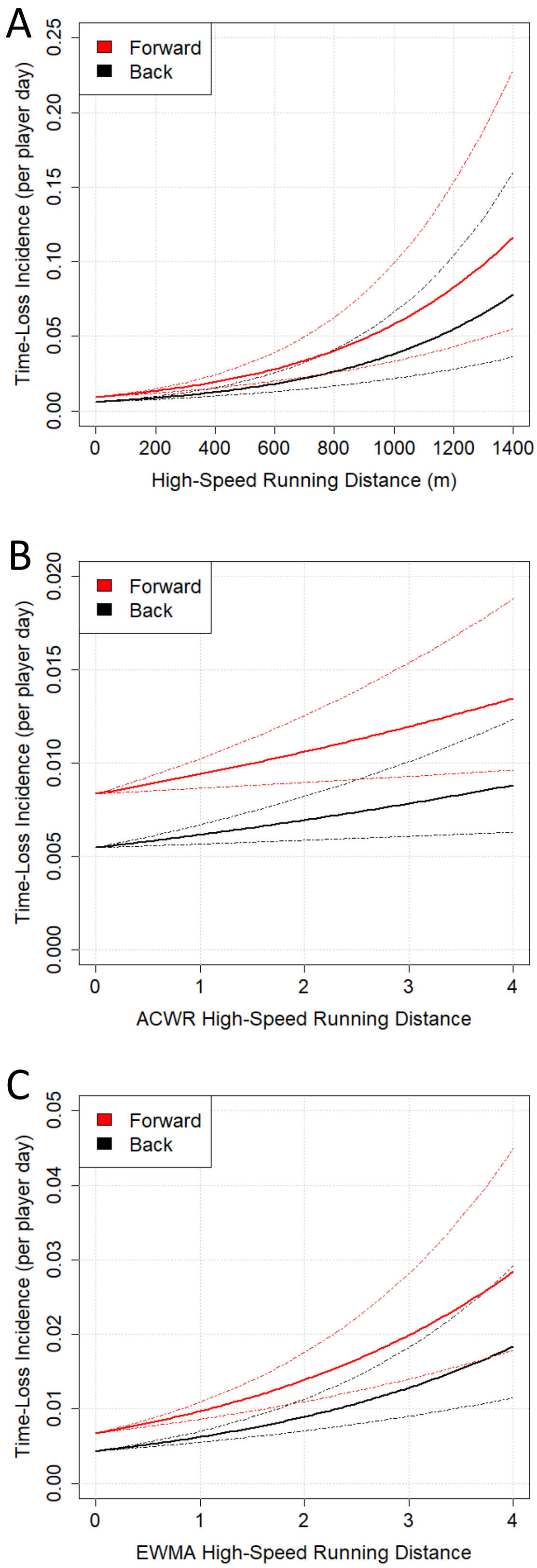


Figure 7.3. The relationship between time-loss incidence occurrence (per player day) and absolute high-speed running distance ($p<0.001$) **(Fig.7.3A)**, ACWR high-speed running distance ($p = 0.154$) **(Fig.7.3B)**, and EWMA high-speed running distance ($p = 0.002$) **(Fig.7.3C)**, split for forwards and backs. Data are mean ± standard error.

7.3.2.4 Cumulative 7, 14, 21, and 28 d Rolling Sums

Mixed effect models were also conducted on the 7, 14, 21, and 28 d cumulative rolling sum data for sRPE load, distance and high-speed running distance. All models returned a non-significant effect on time-loss incidence, with the exception of the 14 d cumulative rolling sum of high-speed running distance (model details (for a 1000 m increase): intercept = -5.301, parameter estimate = 0.300, standard error = 0.100, odds ratio = 1.35, p = 0.040).

7.3.2.5 Comparing Model Fit

To enable a comparison of fit between models containing different variables, all analyses were subsequently performed on a reduced dataset with an equal number of data points for all variables (n = 14937). This dataset was the largest possible dataset where the same number of observations for all nine variables of interest (sRPE load, distance, high-speed running distance and each of these quantified using the ACWR and EWMA approaches) were available. Models were constructed in exactly the same way as above. The AIC and BIC can be used in these models to examine which variable best explains the variance in time-loss incidence occurrence, with smaller AIC and BIC values indicative of a better model fit.

The results of this analysis are shown in Table 7.3. For sRPE load, distance and high-speed running distance, the absolute match and training load variables demonstrated a lower AIC and BIC than when these variables were quantified using either the acute:chronic workload ratio or exponentially weighted moving average approach. This suggests that more of the variance in time-loss incidence occurrence is explained by the absolute match and training load variables rather than when the variables are quantified using either the acute:chronic workload ratio or exponentially weighted moving average. Additionally, the exponentially weighted moving average demonstrated a lower AIC and BIC than acute:chronic workload ratio. When comparing sRPE load, distance and high-speed running distance, the model with sRPE load had the lowest AIC and BIC, followed by distance, then high-speed running distance (Table 7.3).

Table 7.3. Multilevel models examining the impact of the match and training load variables on time-loss incidence (with an equal *n* for all variables), ordered by AIC and BIC as indicators of model fit.

Variable	Variable effect					Position effect			Model characteristics		
	Intercept	Parameter estimate	Std. error	Odds	p-value	Parameter estimate	Odds	p-value	AIC	BIC	Number of observations
sRPE load[$]	-5.431	0.137	0.017	1.15	<0.001	0.407	1.50	0.019	2936	2981	14937
Distance[$]	-5.478	0.160	0.030	1.17	<0.001	0.512	1.67	0.003	2958	3004	14937
HSR distance[$]	-5.255	0.029	0.007	1.03	<0.001	0.497	1.64	0.004	2979	3025	14937
EWMA sRPE load[^]	-6.064	0.206	0.033	1.23	<0.001	0.411	1.51	0.014	2980	3026	14937
EWMA distance[^]	-5.849	0.160	0.041	1.17	<0.001	0.408	1.50	0.014	2980	3026	14937
EWMA HSR distance[^]	-5.439	0.073	0.024	1.08	0.002	0.446	1.56	0.009	2987	3033	14937
ACWR distance[^]	-5.534	0.088	0.033	1.09	0.008	0.425	1.53	0.013	2990	3035	14937
ACWR sRPE load[^]	-5.405	0.068	0.040	1.07	0.090	0.416	1.52	0.015	2993	3038	14937
ACWR HSR distance[^]	-5.206	0.024	0.017	1.02	0.153	0.428	1.53	0.013	2994	3040	14937

Key. AIC: Akaike information criterion; BIC: Bayesian information criterion; ACWR: acute:chronic workload ratio; EWMA: exponentially weighted moving average; HSR: high-speed running. Odds is the exponential of the parameter estimate and represents the increase in risk in time-loss incidence by unit of measure. [$]the parameter estimates, standard error and odds for the absolute load variables are presented for varying increases in units for each variable: sRPE load: 100 AU; distance: 1000 m; high-speed running distance: 10 m (e.g. an increase in sRPE load of 450 AU to 550 AU, etc.). [^]the parameter estimates, standard error and odds for the ratio (ACWR and EWMA) load variables are presented for 0.2-unit increases (e.g. an increase in EWMA sRPE load from 0.8 to 1.0, etc.).

7.3.2.6 Calculating Time-Loss Incidence Rate

The mixed effect models provided here can be used to calculate time-loss incidence. The calculation, using sRPE load as an example, is as follows:

$$\text{Time-loss incidence (per player day)} = \frac{\exp(\text{intercept} + \text{parameter estimate} * \text{sRPE load})}{(1+\exp(\text{intercept} + \text{parameter estimate} * \text{session RPE load})}$$

The above calculation would be for a back. To calculate time-loss incidence in a forward the effect of position must be added to the equation, as follows:

$$\text{Time-loss incidence (per player day)} = \frac{\exp((\text{intercept} + \text{parameter estimate} * \text{sRPE load}) + \text{position parameter estimate})}{(1+\exp((\text{intercept} + \text{parameter estimate} * \text{sRPE load}) + \text{position parameter estimate})}$$

For example, for a forward with a sRPE load of 650 AU, the calculation would be:

$$\frac{\text{Exp}((-5.058 + 0.108 * 650) + 0.280)}{(1+\exp((-5.058 + 0.108 * 650) + 0.280)}$$

$$= 0.017 \text{ time-loss incidences per player day}$$

7.3.2.7 Time-Loss Incidence in Matches and Training

To examine the impact of matches compared to training on time-loss incidence, an additional (match or training) variable was included in the mixed effect models assessing the effect of the absolute match and training load variables on time-loss incidence. There were no interactions between the absolute match and training load variables and matches/training (sRPE load, $p = 0.218$; distance, $p = 0.146$; high-speed running distance, $p = 0.501$). However, there was a significant main effect, suggesting that time-loss incidence was greater in matches compared to training (sRPE load: parameter estimate = 2.313, standard error = 0.235, odds ratio = 10.1, $p<0.001$; distance: parameter estimate = 2.479, standard error = 0.241, odds ratio = 11.9, $p<0.001$; high-speed running distance: parameter estimate = 2.732, standard error = 0.001, odds ratio = 15.4, $p<0.001$).

7.4 Discussion

The aim of the present study was to identify the best predictor of time-loss incidence occurrence between absolute match and training load variables, the acute:chronic workload ratio and the exponentially weighted moving average quantification methods, when applied to sRPE, distance and high-speed running distance. The main findings of the present study suggest that changes in the absolute match and training load variables (sRPE load, distance and high-speed running distance), with no quantification method applied to them, provide the best method of explaining the variance in time-loss incidence rate in elite Rugby Union players. Specifically, the use of absolute sRPE load provided the lowest AIC and BIC values, followed by distance and then high-speed running distance. As shown in Tables 7.2 and 7.3, when comparing the different match and training load quantification methods, the exponentially weighted moving average method better explained the variance in time-loss incidence occurrence than the acute:chronic workload ratio method, as the AIC and BIC were lower across all variables for exponentially weighted moving average compared to acute:chronic workload ratio. A higher time-loss incidence was seen in forwards compared to backs, ranging from 32% (sRPE load) to 62% (distance), but no interaction was seen between position and any match and training load variables. The models examining cumulative rolling sums did not identify any significant effects on time-loss incidence rate of these variables, with the exception being 14 d cumulative rolling sum for high-speed running distance. Overall, these findings suggest that the absolute match and training load variables may provide the best predictors of time-loss incidence rates, with sRPE load likely to be the optimal variant of those examined here.

This is the first study to compare absolute match and training load, acute:chronic workload ratio and exponentially weighted moving average methods for the assessment of time-loss incidence in elite athletes. The model fit assessment suggests that the absolute match and training load variables (sRPE load, distance and high-speed running distance) are better predictors of time-loss incidence occurrence in professional Rugby Union players, compared to when the same variables are quantified using the acute:chronic workload ratio and exponentially weighted moving average approaches. Furthermore, it appears that sRPE load was the best variable to use to assess time-loss incidence (when compared to distance and high-speed running distance). Unlike the GPS-derived variables (distance and high-speed running distance) which require expensive technologies to collect, sRPE load provides performance and medical staff with a low cost, easy to administer method of match and training load assessment and management (Kraft et al., 2014). It is also possible that the RPE variable provides a more accurate reflection of contacts and collisions during Rugby Union (not picked up by GPS variables). Furthermore, RPE was also recorded during gym-based sessions where GPS monitoring is not possible, a further potential explanation of the enhanced predictive ability of the models with RPE included. Additionally, the calculations provided within this paper provide performance and medical staff with actionable values which can be easily communicated to coaches when assessing an individual players risk; and thus, enable them to make an informed decision about player match and training load.

When the two ratio quantification methods (ACWR and EWMA) are compared, the exponentially weighted moving average approach better explains the variance in time-loss incidence occurrence compared to the acute:chronic workload ratio method, as shown through the lower AIC and BIC values. This therefore affirms the thoughts of Menaspa (2017) and Williams et al. (2017) who suggest the acute:chronic workload ratio approach lacks sensitivity and suffers mathematical coupling (Lolli et al., 2017). Furthermore, it agrees with the findings of Murray et al. (2017), who investigated the relationship between match and training load and injury in Australian footballers using only objective (GPS) measures and quantified it using both the acute:chronic workload ratio and exponentially weighted moving average. The present study extends these findings to both subjective (sRPE load) and objective measures and utilised an individual approach to determining high-speed running distance (>70% of an individual's maximum velocity), compared to the set parameters (5.0-6.7 $m{\cdot}s^{-1}$) used by Murray et al. (2017). When assessing the cumulative rolling sums models, the only variable to return a significant effect on time-loss incidence rate was 14 d high-speed running distance, therefore aggregating match and training load into weekly sums does not further assist in time-loss incidence occurrence assessment. To summarise, the absolute match and training load variables better explain the variance in time-loss incidence rates above the ratio acute:chronic workload ratio and exponentially weighted moving average methods and the cumulative rolling sums approach.

The time-loss incidence curves describing the relationships between time-loss incidence and the match and training load variables are shown in Figures 7.1-7.3. In contrast to previous work by Blanch and Gabbett (2016), who suggested that a U-shaped pattern existed between injury incidence and an acute:chronic workload ratio. Our analysis and models do not find any evidence of this form of U-shape pattern. This apparent disagreement in findings may have arisen because the independent variables in the Blanch and Gabbett (2016) analysis appears to be based on aggregated categorical data from a series of research investigations (Hulin et al., 2014; Hulin et al., 2016) whereas in the current study the models use the raw / absolute match and training load data from each player on each day.

Another novel aspect of this study was the comparison in time-loss incidence rates between forwards and backs. Players occupying forward positions were found to have a higher time-loss incidence rates compared to backs for all match and training load variables, ranging from 32 to 62%. An explanation for this may be due to the higher involvement of total impacts, tackles and rucks of forwards compared to backs as shown by Lindsay et al. (2015), and also demonstrated in the results of this paper the number of time-loss incidence occurring through contact injuries makes up 50.0% of all time-loss incidences. Furthermore, it is important to note that position did not interact with any of the match and training load variables, thus suggesting that time-loss incidence rates changed with increased match and training load in a similar manner for both positional groups. In addition, the present study also examined time-loss incidence in training compared to matches. The findings suggest that the likelihood of a time-loss incidence occurring was 10-15 times higher in matches compared to training. However, none of the absolute match and training load variables interacted with the training/match variable, suggesting that the increased time-loss incidence was similar when load increased in both training and matches by a similar amount.

7.4.1 Practical Applications in Rugby Union

The "sweet-spot" of an acute:chronic workload ratio of 0.8-1.3 (based on sRPE load data) suggested by Blanch and Gabbett (2016) has been widely cited and used within professional sport. However, the findings of the present study suggest that the absolute match and training load variables provide a better explanation of the variance in time-loss incidence (and thus should be incorporated in load management models to minimise the time-loss incidences occurring), when compared to the more commonly used acute:chronic workload ratio and exponentially weighted moving average approaches. The present study enhances previous work in the area (Rogalski et al., 2013; Hulin et al., 2016; Cross et al., 2016) by showing that subjective measures (i.e. sRPE load) can be quantified in various ways to manage time-loss incidence. Session RPE load is a relatively inexpensive method when compared to the GPS-derived variables. However, there are obvious challenges associated with the collection of sRPE load data for every player for every session, particularly within 30 min of the end of each session. It should be noted however that evidence has suggested that sRPE is still valid up to 24 h post-exercise (Phibbs et al., 2017), potentially further enhancing the practical utility of sRPE as a monitoring tool. The additional inclusion of objective GPS-based measures can add further value to sRPE load alone by assisting the load management processes due to its capabilities of providing live feedback during training sessions for at risk individuals (e.g., those returning from injury), and may be easier to collect in a large number of players at one time.

7.4.2 Limitations and Future Research

The findings of the present study are based on data from one professional Rugby Union club thus the applicability to all clubs is unknown. Future work could build upon this by, for example, including match and training load and time-loss incidence data from multiple clubs. Furthermore, future work could also consider the relationship between match and training load and different types of time-loss incidence (i.e. contact injuries, non-contact injuries and illness) and whether the injury occurred in training or matches separately. This could potentially allow for greater resolution between variables and quantification methods. However, achieving this volume of data from multiple clubs, allowing such analysis to be undertaken, will be challenging, not least due to the variations in the measurement and management of match and training load and time-loss incidence between clubs. A further potential limitation of the current study was the use of different GPS monitoring systems from season one to season two, as stated in the materials and methods section. Future work should endeavour to use the same GPS monitoring system for the duration of the data collection process to avoid potential conflicts between units. Additionally, future work could also seek to identify the best explanator of the severity of time-loss incidence, subsequently providing support staff (Rugby coaches and performance and medical staff), with the risk (odds) associated with going beyond the thresholds of major severity time-loss incidence. This will be explored in chapter VIII.

7.5 Conclusions

In conclusion, the match and training load variable that best explains the variance in time-loss incidence was absolute sRPE load, followed by absolute distance and absolute high-speed running distance. These findings therefore suggest that the use of absolute match and training load data from each player on each day may be more beneficial when assessing time-loss incidence risk, when compared to the more commonly used acute:chronic workload ratio and exponentially weighted moving average quantification approaches. The objective GPS-derived variables still appeared to provide a significant explanation of the variance in time-loss incidence occurrence, and thus the use of GPS as a real-time monitoring tool (providing live feedback) means that such measures may well have applied utility. When assessing the quantified match and training load variables (ACWR and EWMA), the exponentially weighted moving average variables better explained the variance in time-loss incidence compared to the acute:chronic workload ratio method. No relationship was seen between the 7, 14, 21, and 28 cumulative rolling sums for all variables (sRPE load, distance and high-speed running), with the exception of 14 d cumulative rolling sum of high-speed running distance. Finally, the time-loss incidence curves derived from the mixed effect models (for all absolute, ACWR and EWMA variables) did not show a U-shaped pattern. Overall, these findings suggest that the absolute match and training load variables provide the best predictors of time-loss incidence rates, with sRPE load likely to be the optimal variant of those examined here. Furthermore, the exponentially weighted moving average approach to quantifying match and training load was a better predictor of time-loss incidence risk than when the same variables were calculated using the acute:chronic workload ratio approach.

Chapter VIII
Match and Training Load and the Severity of Time-Loss Incidence in Elite Rugby Union Players

8.1 Introduction

The findings of chapter VII demonstrated that greater levels of match and training load increased the likelihood of time-loss incidence occurrence. Specifically, the findings of chapter VII suggested that the absolute variables best explained the variance in time-loss incidence occurrence; and in particular the absolute session rating of perceived exertion (sRPE load) explained the most variance in time-loss incidence occurrence. Additionally, the match and training load variables quantified using the exponentially weighted moving average (EWMA) approach were a better predictor of time-loss incidence occurrence than when the same variables were calculated using the acute:chronic workload ratio (ACWR) approach.

Whilst assessing time-loss incidence occurrence is of great importance, another important factor to consider is the severity of the time-loss event (i.e. the number of days before a player can return to training and be available for match selection). This is a key concern given that player availability is a key determinant of successful team performance (Carling et al., 2015). Extending beyond time-loss incidence occurrence, the severities associated with the related injuries and illnesses will provide practitioners with greater information regarding the risk of increased match and training load exposures. Therefore, the aim of chapter VIII was to investigate the influence of match and training load exposure on the severity of time-loss incidence in elite Rugby Union players. Coaches and support staff may accept the risk of going beyond thresholds of load for low severity (minor: ≤7 d) time-loss incidence in the pursuit of increased performance (Jones et al., 2017). Therefore, an understanding of the relationship between match and training load on not only time-loss occurrence but also the severity, will allow applied practitioners to make informed decisions.

Previous injury- and illness-based studies assessing match and training load have focused on the incidence of these events, rather than the severity of the injuries and illnesses that occur (Rogalski et al., 2013; Colby et al., 2014; Chapter VII). The limited research to date exploring the severity of time-loss incidence in professional Rugby Union has been confined to simply stating the average days missed due to injury and whether the injury was minor (≤7 d lost) or major (≥8 d lost), rather than investigating the factors affecting the severity of the injury (Brooks et al., 2005a; Brooks et al., 2005b). A two-season study of match and training injuries from 546 Rugby Union players from 12 English Premiership clubs was undertaken, with the overall incidence of injury and severities reported (Brooks et al., 2005a; Brooks et al., 2005b). The average number of days lost to all injuries for all positions for match injuries was 18 d (95% CI: 16, 20 d) and for training injuries was 24 d (95% CI: 20, 27 d). However, the factors affecting the severity of injury (e.g. match and training load) were not considered.

Match and training load quantified using objective (global positioning systems (GPS)) and subjective (session ratings of perceived exertion (sRPE)) methods are common practice in elite sporting environments (Rogalski et al., 2013; Colby et al., 2014). Previous research has measured load using the subjective sRPE load (Foster et al., 2001) and objective GPS variables (e.g. distance and high-speed running distance; Colby et al., 2014). However, few studies have utilised or compared both methods; despite the fact that such work would prove valuable for an applied practitioner looking to select the optimum load monitoring tool. A number of different methods have then subsequently been used to quantify both subjective and objective measures of match and training load. The four most common methods are absolute match and training load, the acute:chronic workload ratio (ACWR), the exponentially weighted moving average (EWMA) approach and the rolling 7, 14, 21, and 28 d cumulative sums (Blanch and Gabbett, 2016; Williams et al., 2017). The findings of chapter VII demonstrate that the absolute match and training load variables best explained the variance in time-loss incidence occurrence, with the exponentially weighted moving average quantification method more sensitive to the variance than the commonly used acute:chronic workload ratio approach. However, the effect of match and training load, and more specifically the best method of quantification, on the severity of time-loss incidence has not been considered in the literature to date.

Therefore, the aims of the present study were to examine and identify relationships between match and training load, derived through both subjective and objective measures, and the severity of time-loss incidence in elite Rugby Union players. The assessment of how match and training load influence the severity of time-loss incidence is novel. Furthermore, this study will also examine the load variable (sRPE load, distance and high-speed running distance) and quantification method (absolute load, ACWR, EWMA and cumulative sums) that best explains the variance in the severity of time-loss incidence. It will test the hypothesis that as match and training load increases, the likelihood of sustaining a major severity time-loss incidence will also increase. Furthermore, based on the findings of chapter VII, it will test the hypothesis that the absolute and exponentially weighted moving average methods of load quantification will better explain the variance in severity of time-loss incidence compared to the acute:chronic workload ratio method.

8.2 Methodology

8.2.1 Study Design

The cohort of Rugby Union players examined in this study is consistent with the other chapters presented in this thesis (n = 89). Participant characteristics can be found in the general methods (Chapter III). In brief, the quantification of load was undertaken using four methods; the absolute match and training load (cumulative daily load), the acute:chronic workload ratio (Blanch and Gabbett, 2016), the exponentially weighted moving average (Williams et al., 2017) and rolling cumulative sum (7, 14, 21, and 28 d). These calculations were applied to subjective (sRPE load) and objective (GPS; distance and high-speed running distance) variables.

8.2.2 Rating of Perceived Exertion (RPE)

For every field-based training session and match, an RPE rating, using the modified Borg CR-10 RPE scale (Foster et al., 2001), was obtained within 30 min of the end of the exercise, in line with the recommendations of Kraft et al. (2014). Session RPE load (sRPE load) in arbitrary units (AU) was then calculated for each player by multiplying the given RPE by the session duration (min) (Foster et al., 2001). This was performed for all players across both seasons of data collection. The collection of RPE data was consistent across all experimental chapters and additional information on the validity and reliability of sRPE for estimating relative exercise intensity can be found in the general methods (Chapter III). The acute:chronic workload ratio and exponentially weighted moving average calculations were then applied to the RPE data, yielding two variables: ACWR sRPE load and EWMA sRPE load. In addition, cumulative 7, 14, 21, and 28 d sums were calculated.

8.2.3 Global Positioning Systems (GPS)

An objective measure of match and training load was obtained through GPS for every field-based training session and match. The assignment, validity and reliability, software and horizontal dilution of precision information of the GPS data collection can be found in the general methods (Chapter III). Total distance and high-speed running distance (set at greater than 70% of an individual player's maximum velocity) were the two objective GPS-derived variables used throughout this study. Additional information on the determination of high-speed running threshold can be found in the general methods (Chapter III). GPS data were also quantified using acute:chronic workload ratio and exponentially weighted moving average, giving rise to four further variables (ACWR distance, EWMA distance, ACWR high-speed running distance and EWMA high-speed running distance). In addition, the cumulative 7, 14, 21, and 28 d rolling sums were calculated for both distance and high-speed running distance.

8.2.4 Time-Loss Incidence Definitions

All time-loss incidences sustained were categorised by the club's medical staff and were defined as any physical complaint that resulted in that individual being unable to take a full part in any field- or gym-based training session or match, in line with the consensus statement defined by the International Rugby Board in 2007 (Fuller et al., 2007a). Further information on the nature of the time-loss incidence was recorded, including severity (number of days unavailable for training and/or matches), the modality of the injury (contact, non-contact or illness) and the session in which the injury occurred (training or match). The severity of time-loss incidence was based upon the number of days that a player was unavailable for training and/or matches, and was categorised as either minor (≤7 d) or major (≥8 d) based on the work of Brooks et al. (2005a), to ensure consistency with Rugby Union literature. Each time-loss incidence (and its related severity (minor or major)) was entered into the database for the day on which it occurred and was subsequently associated with the absolute match and training load, acute:chronic workload ratio, exponentially weighted moving average or cumulative rolling sum for that day.

8.2.5 Statistical Analysis

The first section of the results presents descriptive data on the severities on time-loss incidences. To assess the impact of each match and training load variable and the quantification method on the severity of time-loss incidence, mixed effect models were conducted using the *glmer* function (as suggested by Windt et al., 2018). All analyses were performed using the R software package (www.r-project.org). All models were fit with a Bernoulli outcome distribution (i.e., minor [≤7 d] or major [≥8 d]), with position (forward or back) included in all models. Player ID, day of the season, and season number were controlled for in all models. The exponential of the parameter estimate was used to calculate the odds ratio (OR) of sustaining a major severity time-loss incidence compared to one of minor severity. Subsequently, 95% CI (1.96 * standard error) were also calculated.

Due to co-linearity between the independent variables, it was not possible to include several within the same model. Thus, separate models were performed for each variable. Subsequently, to enable a comparison of fit between models containing different numbers of data points (arising due to the ACWR and EWMA variables requiring at least 28 d of match and training load data and the cumulative sums requiring 7, 14, 21, and 28 d respectively), all analyses were performed on a reduced dataset with an equal number of data points for all variables (n = 326). In these models, the Akaike information criterion (AIC) and Bayesian information criterion (BIC) were used to assess model fit. For all analyses, statistical significance was accepted as $p<0.05$ and data are presented as mean ± 95% CI.

8.3 Results

8.3.1 Descriptive Data

A total of 474 time-loss incidences were reported across the two seasons of the study with an average severity of 21 d (95% CI: 17 d, 25 d). Table 8.1 details the severities (days lost) for all time-loss incidences, injuries (and split by match, training, contact and non-contact injuries) and illnesses for the seasons combined. Additionally, Table 8.1 demonstrates the number of minor and major severity time-loss incidences. When assessing minor (≤7 d) compared to major (≥8 d) severities, 57.0% of all time-loss incidences were minor, with 43.0% classified as major. While observing just injuries, it was almost a 50:50 split, with 50.5% of the injuries resulting in ≥8 days lost (major). Match injuries had a tendency towards major severity (53.3%), whereas a greater number of training injuries were of minor severity (54.5%). Similarly, contact injuries had a tendency towards major severity (52.7%), with a greater number of non-contact injuries of minor severity (52.7%). Illnesses of minor (≤7 d) severity accounted for 98.6% of all cases.

Table 8.1. Severity (number of days lost) and the number (and percentage) of minor and major severity events for all time-loss incidences, injuries, match injuries, training injuries, contact injuries, non-contact injuries and illnesses. Severity data are presented as mean (95% CI) and the frequency expressed both as absolute number and a percentage of each category.

Type of incidence	Severity (d) (95% CI)	Frequency	
		Minor (≤7 d)	Major (≥8 d)
All time-loss incidences	21 (17, 25)	270 (57.0%)	204 (43.0%)
All injuries	24 (20, 28)	199 (49.5%)	203 (50.5%)
Match injuries	26 (21, 32)	120 (46.7%)	137 (53.3%)
Training injuries	13 (9, 18)	79 (54.5%)	66 (45.5%)
Contact injuries	25 (20, 30)	112 (47.3%)	125 (52.7%)
Non-contact injuries	18 (11, 24)	87 (52.7%)	78 (47.3%)
Illnesses	2 (2, 2)	71 (98.6%)	1 (1.4%)

8.3.2 Mixed Effect Models

Results of the mixed effect models that were conducted to examine the impact of each match and training load variable on the severity of time-loss incidence (minor vs. major) are presented in Table 8.2. There was no effect for age or session (whether the injury occurred in a match or training) (all $p>0.05$); thus, these variables were removed from the models. Position (forward vs. back) did not interact with any of the match and training load variables to influence severity (so interactions were removed from all models). However, position did demonstrate a main effect on the severity outcome; thus, the main effect was included in all models.

8.3.2.1 Session RPE Load

sRPE load demonstrated a significant influence on the severity of time-loss incidence ($p = 0.028$; Table 8.2). The odds of 1.06 indicates that for each 100 AU increase in sRPE load (e.g. from 700 to 800 AU), there was a 6% increase in the likelihood of sustaining a major severity time-loss incidence compared to a minor severity time-loss incidence. ACWR sRPE load also demonstrated an influence on the severity of time-loss incidence ($p = 0.009$). For every 0.2 unit increase in the ratio (e.g. from 1.4 to 1.6), there was a 22% increase in the likelihood of sustaining a major severity time-loss incidence (OR = 1.22). Additionally, the EWMA sRPE load variable also had an influence on the severity of time-loss incidence ($p<0.001$). For every 0.2 unit increase (e.g. from 0.8 to 1.0), resulted in a 36% increase in the likelihood of sustaining a major severity time-loss incidence (OR = 1.36).

8.3.2.2 Distance

Absolute distance demonstrated a significant influence on the severity of time-loss incidence ($p = 0.011$; Table 8.2). The odds of 1.13 demonstrate that for every 1000 m increase in absolute distance (e.g. from 1250 m to 2250 m), there was an 13% increase in the likelihood of a major severity time-loss incidence occurring. ACWR distance did not influence the odds of major severity time-loss incidence ($p = 0.852$). However, when quantified using the exponentially weighted moving average approach, an influence on the severity of time-loss incidence was seen (p = 0.001). The odds of 1.32 demonstrate that for every 0.2 unit increase in EWMA distance (e.g. from 0.6 to 0.8) there was a 32% increase in major severity probability compared to a minor severity time-loss incidence.

8.3.2.3 High-Speed Running Distance

There was no effect of high-speed running distance, using any of the three quantification methods, on the severity of time-loss incidence (absolute high-speed running distance, p = 0.795; ACWR high-speed running distance, p = 0.351; EWMA high-speed running distance, p = 0.241; Table 8.2).

8.3.2.4 Position Effect

When considering all models, the odds of a back incurring a major severity time-loss were lower compared to forwards for all variables and quantification methods (OR range from 0.46 to 0.73; p values range from 0.016 to 0.133; Table 8.2). The inverse of the odds ratios can be used to calculate the odds of a forward sustaining a major severity time-loss incidence compared to a back. For example, in the sRPE load model (Table 8.2), the odds of a forward sustaining a major time-loss incidence compared to a back is 1.39 (i.e. 1 / 0.72 = 1.39).

8.3.2.5 Cumulative 7, 14, 21, and 28 d Rolling Sums

Mixed effect models were also conducted on the 7, 14, 21, and 28 d cumulative rolling sum data for sRPE load, distance and high-speed running distance. All models returned a non-significant effect on the likelihood of major severity time-loss incidence (compared to minor severity), with the exception of the 7 d and 14 d cumulative rolling sum of distance (model details: 7 d distance: intercept = 0.701, parameter estimate = 0.053, standard error = 0.019, OR = 1.05, p = 0.005; 14 d distance: intercept = -0.664, parameter estimate = 0.028, standard error = 0.010, OR = 1.03, p = 0.004); with the parameter estimate, standard error and odds ratio presented for a 1000 m increase in distance.

Table 8.2. Multilevel models examining the impact of match and training load variables on time-loss incidence severity.

Variable	Variable effect					Position effect			Model characteristics		
	Intercept	Parameter estimate	Std. error	Odds	p-value	Parameter estimate	Odds	p-value	AIC	BIC	Number of observations
sRPE load$	-0.445	0.062	0.062	1.06	0.028	-0.322	0.72	0.133	651	676	474
ACWR sRPE load^	-1.203	0.198	0.076	1.22	0.009	-0.411	0.66	0.093	587	611	432
EWMA sRPE load^	-1.772	0.306	0.085	1.36	<0.001	-0.422	0.66	0.075	581	605	432
Distance$	-0.379	0.125	0.049	1.13	0.011	-0.622	0.54	0.018	499	523	366
ACWR distance^	0.126	-0.013	0.069	0.99	0.852	-0.746	0.47	0.020	448	471	326
EWMA distance^	-1.523	0.278	0.085	1.32	0.001	-0.687	0.50	0.022	437	460	326
HSR distance$	-0.054	-0.003	0.012	1.00	0.795	-0.528	0.59	0.054	505	529	366
ACWR HSR distance^	0.244	-0.037	0.040	0.96	0.351	-0.730	0.48	0.022	448	470	326
EWMA HSR distance^	-0.246	0.061	0.052	1.06	0.241	-0.774	0.46	0.016	447	470	326

Key. AIC: Akaike information criterion; BIC: Bayesian information criterion; ACWR: acute:chronic workload ratio; EWMA: exponentially weighted moving average; HSR: high-speed running. Odds is the exponential of the parameter estimate and represents the increase in risk in severity of time-loss incidence by unit of measure. $the parameter estimates, standard error and odds for the absolute load variables are presented for varying increases in units for each variable: sRPE load: 100 AU; distance: 1000 m; high-speed running distance: 10 m (e.g. an increase in sRPE load of 450 AU to 550 AU, etc.). ^the parameter estimates and odds for the ratio (ACWR and EWMA) load variables are presented for 0.2-unit increases (e.g. an increase in EWMA sRPE load from 0.8 to 1.0, etc.).

8.3.2.6 Comparing Model Fit

To enable a comparison of fit between models containing different variables, all analyses were subsequently performed on a reduced dataset with an equal number of observations for all variables (n = 326). This dataset was the largest possible dataset where all time-loss incidences contained all nine variables of interest were available (sRPE load, distance and high-speed running distance, each quantified using the absolute, ACWR and EWMA approaches). Models were constructed in exactly the same way as above. The AIC and BIC can be used in these models to examine which variable best explains the variance in the severity of time-loss incidence occurrence, with smaller AIC and BIC values indicative of a better model fit.

The results of this analysis are shown in Table 8.3. The same five load quantification methods (absolute sRPE load, ACWR sRPE load, EWMA sRPE load, absolute distance and EWMA distance) influenced the severity of time-loss incidence in the equal n dataset, as they did in the full observation models presented above. When assessing the model fit, the AIC and BIC for EWMA sRPE load demonstrated the lowest values, followed by EWMA distance, absolute distance, absolute sRPE load and ACWR sRPE load. This would suggest that more of the variance in the severity of time-loss incidence is explained by the exponentially weighted moving average and absolute load quantified variables above the acute:chronic workload ratio quantified variables (Table 8.3).

Table 8.3. Multilevel models examining the impact of match and training load variables on time-loss incidence (with an equal *n* for all variables), ordered by AIC and BIC as indicators of model fit.

Variable	Variable effect					Position effect			Model characteristics		
	Intercept	Parameter estimate	Std. error	Odds	p-value	Parameter estimate	Odds	p-value	AIC	BIC	Number of observations
EWMA sRPE load^	-1.878	0.359	0.106	1.43	<0.001	-0.738	0.48	0.017	436	459	326
EWMA distance^	-1.523	0.278	0.085	1.32	0.001	-0.687	0.50	0.022	437	460	326
Distance$	-0.367	0.154	0.053	1.17	0.004	-0.820	0.44	0.007	440	463	326
sRPE load$	-0.382	0.091	0.035	1.09	0.011	-0.737	0.48	0.017	442	465	326
ACWR sRPE load^	-1.111	0.219	0.096	1.24	0.024	-0.739	0.48	0.019	443	466	326
EWMA HSR distance^	-0.246	0.061	0.052	1.06	0.241	-0.774	0.46	0.016	447	470	326
ACWR HSR distance^	0.244	0.037	0.040	1.04	0.351	-0.730	0.48	0.022	448	470	326
HSR distance$	0.071	-0.004	0.013	1.00	0.768	-0.732	0.48	0.023	448	471	326
ACWR distance^	0.126	-0.013	0.069	0.99	0.852	-0.746	0.47	0.020	448	471	326

Key. AIC: Akaike information criterion; BIC: Bayesian information criterion; ACWR: acute:chronic workload ratio; EWMA: exponentially weighted moving average; HSR: high-speed running. Odds is the exponential of the parameter estimate and represents the increase in risk in severity of time-loss incidence by unit of measure. $the parameter estimates, standard error and odds for the absolute load variables are presented for varying increases in units for each variable: sRPE load: 100 AU; distance: 1000 m; high-speed running distance: 10 m (e.g. an increase in sRPE load of 450 AU to 550 AU, etc.). ^the parameter estimates and odds for the ratio (ACWR and EWMA) load variables are presented for 0.2-unit increases (e.g. an increase in EWMA sRPE load from 0.8 to 1.0, etc.).

8.4 Discussion

The aim of the present study was to identify the effect of match and training load on the severity of time-loss incidence in elite Rugby Union players. A secondary aim was to examine which method of match and training load quantification (absolute, ACWR, EWMA and cumulative rolling sum; applied to sRPE load, distance and high-speed running distance) best explained the variance in severity of time-loss incidence. The main finding of the present study suggests that a greater match and training load increases the likelihood of a major, compared to a minor, severity time-loss incidence occurring. Furthermore, another key finding of the present study was that match and training load quantified using the exponentially weighted moving average method best explains the variance in the likelihood of sustaining a major time-loss incidence compared to one of minor severity, in elite Rugby Union players. Specifically, the use of EWMA sRPE load provided the lowest AIC and BIC values, followed by EWMA distance and absolute distance (Table 8.3). The models examining the cumulative rolling sums did not identify any significant effects on the severity of time-loss incidence with the exception of 7 d and 14 rolling sums for distance. Overall, these findings suggest that a greater match and training load is associated with a higher risk of a major time-loss incidence occurring, and that the match and training load variables quantified using the exponentially weighted moving average method may provide the best predictors of major time-loss incidence.

The main finding of the present study suggests that a higher match and training load exposes players to a greater risk of sustaining a major, compared to a minor, severity time-loss incidence. For every unit increase in load (with the exception of ACWR distance and ACWR high-speed running distance), increased odds of sustaining a major severity time-loss incidence was seen (Table 8.2). As this was the first study to examine the influence on match and training load on the severity of time-loss incidence in elite Rugby Union players this is an important finding. The practical utility of this finding, along with those discussed below, provides support staff with the tools to manage match and training load in order to reduce the likelihood of a major severity time-loss incidence occurring. Furthermore, the relationship between higher squad availability and the increased prospect of successful performance

(Williams et al., 2016) supports the notion that sustaining a minor time-loss incidence will have less of an impact on team performance than one of major severity.

In the present study, sRPE load best explained the variance in the severity of time-loss incidence compared to distance and high-speed running distance, as demonstrated in the AIC and BIC values of Table 8.3. This is therefore in agreement with the findings of chapter VII, where the sRPE load variable was the best indicator of the occurrence of time-loss incidence. Unlike the GPS-derived variables, which require expensive technologies to collect, sRPE load provides performance and medical staff with a low-cost method of match and training load assessment and management (Kraft et al., 2014). The subjective, sRPE method of load assessment can also recorded during gym-based sessions where GPS monitoring is not possible, a further potential explanation of the enhanced predictive ability of the models with sRPE included and its practical utility. Furthermore, the three sRPE variables (absolute, ACWR and EWMA) explained the variance in the severity of time-loss incidence (all $p<0.05$). Therefore, reaffirming its practical function with any quantification method and the requirement for gym-based loads (and all load not accounted for using GPS units) to be included as part of load management protocols adopted by elite sports clubs. It should be noted that sRPE can be challenging to collect effectively in large team sports environments, therefore it needs to be recognised by staff and players otherwise the data quality will be affected, and the practical value of the method curtailed. Nonetheless, it is likely that this more holistic approach enables support staff to make better, more informed, decisions about individual player match and training load.

This is also the first study to compare the application of different quantification methods (absolute, ACWR, EWMA and cumulative rolling sum) of match and training load variables, for the assessment of the severity of time-loss incidence in elite athletes. Results of the equal n models (Table 8.3) indicate that the match and training load variables quantified using the exponentially weighted moving average approach best explain the variance in the severity of time-loss incidence, compared to the absolute and acute:chronic workload ratio quantification methods. This is again in agreement with the findings of Chapter VII, where the exponentially weighted moving average method was a better indicator of the variance than the more commonly used acute:chronic workload ratio approach (Chapter VII; Table 7.3).

Concerns have previously been raised regarding the acute:chronic workload ratio method of load quantification (Menaspa, 2017; Lolli et al., 2017; Williams et al., 2017; Lolli et al., 2018), such as flaws in its mathematical underpinning subsequently leading to spurious correlations and the lack of acknowledgement for the decaying nature of fitness and fatigue overtime. Therefore, it was hypothesised that the exponentially weighted moving average method would be more sensitive to the changes in load and therefore act as a better predictor of the occurrence of time-loss incidence than the acute:chronic workload ratio method. This has consequently been confirmed with the findings from chapter VII (occurrence). The findings of this study extend this to demonstrate the increased sensitivity of the exponentially weighted moving average approach when explaining the variance in the severity of time-loss incidences.

Another novel aspect of this study was the comparison in the severity of time-loss incidence between forwards and backs. A greater likelihood of major severity time-loss incidence (compared to minor time-loss incidence occurrence) was seen for the forwards compared to the backs ranging from odds of 1.39 (absolute sRPE load) to odds of 2.17 (EWMA high-speed running distance). The reason for the increased likelihood in forwards is unknown and warrants further investigation. The findings of chapter V suggest it is not due to the greater exposure in key performance indicator variables (such as tackles made). It is important to note that position did not interact with any of the match and training variables, thus suggesting that the severity of time-loss incidence changed with increased match and training load in a similar manner for both positional groups, yet was higher in forwards for any given match and training load.

The final novel aspect of this study was the inclusion of illnesses alongside injury when assessing the impact of match and training load on the severity of time-loss incidence. The key finding was that almost all illnesses (98.6%) were minor (≤7 d lost) in severity. Therefore, this suggests that reducing injury incidence (particularly major severity), as opposed to illness incidence, would have a greater influence on squad availability, match selection and, subsequently, enhance team performance (Williams et al., 2016).

8.4.1 Practical Applications in Rugby Union

The use of the acute:chronic workload ratio suggested by Blanch and Gabbett (2016) has been widely cited and used within professional sport for the management of match and training load to reduce time-loss incidence occurrence and enhance player availability. However, the findings of the present study promote the use of the exponentially weighted moving average approach to match and training load management, due to its greater sensitivity in explaining the variance in the severity of time-loss incidences. Specifically, EWMA sRPE load best explains the variance in the severity of time-loss incidence (and thus should be incorporated in load management models to minimise major severity time-loss incidence), when compared to the more commonly used acute:chronic workload ratio approach. The present study extends the previous work in the area (e.g. Rogalski et al., 2013; Cross et al., 2016) by being the first to demonstrate how subjective measures (i.e. sRPE load) can be quantified using exponentially weighted moving average and/or absolute load methods to assess the severity of time-loss incidence. Furthermore, the sRPE method of load quantification is relatively inexpensive in comparison to GPS-derived variables and can therefore be utilised by all sports teams across the spectrum of professionalism. The current study also demonstrates how the use of GPS-derived variables (such as distance) can be used in models to assess the risk of major severity time-loss incidence and may add further to the sRPE load method alone, due to its capabilities of providing live feedback during both training sessions and matches for at risk individuals (e.g. those returning from injury).

8.4.2 Limitations and Future Research

Whilst the present study is novel in its consideration of how match and training load affect the severity of time-loss incidences, a limitation could be that it is based on data from one professional Rugby Union club; thus, its applicability to all clubs is unknown. Future work could attempt to include match and training load data from multiple clubs, whilst also considering the relationships between match and training load and different types of time-loss incidence and their respective severities separately (i.e. contact injuries, non-contact injuries and illness; match injuries and training injuries). However, achieving this volume of data from multiple clubs, allowing for such analyses, will be challenging, not least due to the variations in the measurement of match and training load and definition of time-loss incidence between clubs.

8.5 Conclusions

The main finding of the present study was that exposure to greater match and training load increased the likelihood of a major, compared to a minor, severity time-loss incidence occurring. Furthermore, match and training load quantified using the exponentially weighted moving average method, specifically EWMA sRPE load, best explained the variance in severity of time-loss incidence in elite Rugby Union players. These findings therefore demonstrate the benefits of using exponentially weighted moving average match and training load variables when assessing the severity of time-loss incidence, and consequently emphasise that these variables should be incorporated into load management protocols. Whilst the subjective measure of sRPE load best explained the variance in the severity of time-loss incidences, the practical utility of GPS-derived running variables and their capability of providing live feedback means it should not be overlooked as a monitoring aid.

Chapter IX
General Discussion

9.1 Overview of Key Findings

A summary of the key findings of the studies presented in this thesis are as follows:

- The running demands of Rugby Union were higher for backs, compared to forwards, in both training (on average by 704 m per session) and matches (distance: by 7.6 $m \cdot min^{-1}$; high-speed running distance: by 1.22 $m \cdot min^{-1}$) (Chapter IV).

- The contact actions of matches were higher in forwards. The forwards made more tackles (78%), tackle assists (207%), breakdown entries (324%) and had more total contact events (117%), compared to the backs (Chapter IV).

- When comparing training demands of the Premiership and Championship seasons; the sRPE load demand of training was higher (on average by 16 AU) in the Championship, whilst the distance covered per training session was higher (on average by 191 m) in the Premiership (Chapter IV).

- When comparing the match demands of the Premiership and Championship; the high-speed running demands were greater (on average by 0.17 $m \cdot min^{-1}$) in the Premiership compared to the Championship The Premiership also had a greater defedning demand (53% more tackles made and 35% more tackles missed) whereas the Championship had a greater attacking demand (14% more contact carries and 11% more breakdown entries) (Chapter IV).

- Overall match injury incidence rate was 137.2 injuries per 1000 match exposure hours, with head/face (21.7 per 1000 h) and knee (21.7 per 1000 h) the most common sites of match injury incidence. The incidence of contact injuries was higher than the incidence of non-contact injuries in matches (119.4 per 1000 h vs. 17.8 per 1000 h, respectively), with non-contact injury incidence almost exclusively occurring in the lower body. However, key performance indicator variables (such as tackles made, tackle assists, tackles missed, contact carries, breakdown entries and contact events) did not affect match injury incidence (Chapter V).

- A playing surface containing any synthetic content (i.e. fully synthetic or hybrid) approximately doubled the odds of sustaining a match injury, compared to natural grass pitches (hybrid: OR = 2.58, $p<0.001$; synthetic: OR = 2.16, $p = 0.033$). The odds of sustaining a contact injury on an artificial playing surface was more than double that on a natural grass pitch (hybrid: OR = 2.31, $p = 0.001$; synthetic: OR = 2.19, $p = 0.049$), whilst the odds of sustaining a non-contact injury was four times greater on the hybrid playing surface compared to natural grass (OR = 4.18, $p = 0.028$) (Chapter VI).

- Absolute match and training load variables (sRPE load, distance and high-speed running distance), with no quantification method applied to them, provided the best method of explaining the variance in time-loss incidence occurrence. More specifically, the absolute sRPE load variable provided the lowest AIC and BIC values and was therefore the best predictor of time-loss incidence occurrence (Chapter VII).

- The exponentially weighted moving average method of load quantification better explained the variance in time-loss incidence occurrence than the acute:chronic workload ratio method, as indicated by lower AIC and BIC values (Chapter VII).

- Greater match and training load exposure increased the likelihood of sustaining a major (≥8 d lost) severity time-loss incidence compared to one of minor (≤7 d lost) severity. Specifically, match and training load quantified using the exponentially weighted moving average method best explained the variance in severity of time-loss incidence, returning lower AIC and BIC values compared to the absolute and acute:chronic workload ratio methods. The best load assessment method for explaining the variance in the severity of time-loss incidence was sRPE load quantified using the exponentially weighted moving average approach (Chapter VIII).

The following discussion analyses these points with respect to previous literature and draws together the findings of the experimental studies presented in this thesis. Furthermore, the practical applications that can be derived from the findings of this thesis are discussed, making reference to their utility for sport and exercise science practitioners working in elite Rugby Union.

9.2 Match and Training Demands of Elite Rugby Union

9.2.1 Match Demands

Chapter IV of this thesis presents the match demands of the two main positional groups (i.e. forwards and backs) within the top two tiers of professional Rugby Union in England (Premiership and Championship). The unique opportunity to investigate the demands of matches (and training) across these two leagues of competition within the same cohort presented itself, and the findings are therefore novel and insightful for applied practitioners working in elite Rugby Union. In matches, the backs covered more distance (on average by 7.6 $m \cdot min^{-1}$) and more high-speed running distance (on average by 1.22 $m \cdot min^{-1}$) compared to forwards. The Premiership high-speed running distance demand in matches was also greater than that of the Championship (on average by 0.17 $m \cdot min^{-1}$). Differences in match key performance indicator (such as the number of tackles) variables between the positional groups and levels of competition were found. Forwards averaged more tackles, tackle assists, breakdown entries and contact events compared to backs. The Premiership demand from a defensive stance (tackles and missed tackles) was higher than that of the Championship, whereas the attacking demand (contact carries and breakdown entries) was higher in the Championship compared to the Premiership.

The differences in match demands between the Premiership and Championship could be as a result of the generally higher standard of play om the Premiership. However, it is also important to consider that such differences may be due to differences in match outcome. The club studies in this thesis was promoted and relegated between the two leagues of competition during the course of the study (England Rugby, 2020). It is possible that defending for prolonged periods of time (in the Premiership) insinuates a team under pressure from the opposition and subsequently susceptible to conceeding points and returning a negative match outcome. Conversely, in the Championship, the team was more succesful and thus completing more ball carries and breakdown entries, to create quick ball in attack it to be expected.

The difference in running demands of matches was clear; the backs accumulate greater distance and high-speed running distance in comparison to the forwards. Subsequently, this finding will allow practitioners to create training protocols in alignment with match demands, thus allowing position specific prepardness (Gabbett, 2015). This is further demonstrated in section 9.2.2, where the backs covered on average greater distances in training compared to the forwards, therefore in alignment with the match demands. In matches, the greater high-speed running demands associated with the backs position is conducive of the physiological characteristics of those players; faster maximum speeds and a lower body fat percentage, thus, advantageous for producing higher speed outputs and accumulating greater amounts of high-speed running distances (Smart et al., 2013). Of the three load variables investigated (sRPE load, distance and high-speed running distance), high-speed running distance was the only variable to present a difference in demand between the leagues of competition. Players on average covered 0.17 $m \cdot min^{-1}$ more high-speed running distance in the Premiership compared to the Championship. Although no study has yet sought to identify physical differences between the players of the Premiership and Championship, by virtue of the higher playing division, the players operating in the Premiership may be physically superior to that of the Championship and therefore produce higher speed / power outputs than that of their Championship counterparts. Additionally, Premiership players may characteristically possess higher maximum speeds compared to their Championship counterparts, therefore, accumulating greater high-speed running distances (set at 70% of the individual players maximum velocity), means they accumulate more high-speed running distance at a higher absolute velocity.

Another novel aspect of the study presented in chapter IV was the direct comparison between the key performance indicator variable demands by position (forward vs. back) and league of competition (Premiership vs. Championship). When assessing disparities between the forward and back positions the forwards made a greater number of tackles (78%), greater number of tackle assists (207%), a greater number of breakdown entries (324%) and were involved in a greater number of contact events (117%). The number of tackles missed, and number of contact carries was not different between the positional groups. These findings are in agreement with those of southern-hemisphere Super 15 matches, where it was demonstrated that forwards were involved in more impacts, tackles and rucks compared to backs, as a result of their proximity to the tackle / breakdown contest. Thus, it is logical that the physiological profile of forwards is more suited to the actions associated with tackling and the breakdown, contrary to the backs where, as previously mentioned, the running load demands outweigh the importance of contact actions (Lindsay et al., 2015; Quarrie et al., 2013). Therefore summarising, the close quarters contact elements of Rugby Union are completed predominantly by forwards, whereas the distance and high-speed running distance demands, are higher for the backs. This thesis confirms the differences in demand between the positional groups and, for the first time, quantifies these differences, in both matches and training, for elite Rugby Union players.

9.2.2 Training Demands

In addition to considering the match demands associated with elite Rugby Union, this thesis also assessed the training demands (Chapter IV). This thesis demonstrated how the running demands were higher for the backs compared to the forwards (on average by 704 m per session) and the overall training demand from a running perspective (distance) was higher in the Premiership season compared to the Championship season (on average by 191 m per session). The increased focus on technical/tactical skills required in the Premiership may be a contributing factor to the increased training demands associated with that season. Due to the increased level of competition, the training sessions undertaken during the Premiership campaign are typically longer in duration and contained greater amounts of positional specific preparation. The units sessions (where players were split in to forwards and backs to train separately) are designed to allow players to concentrate on the positional specific elements of match play. For example, the forwards complete numerous repetitions of lineouts, scrums and breakdown work whereas the backs carry out set play sequences and back field coverage drills. Given the requirement of these drills, it is therefore unsurprising that the backs covered a greater distance than the forwards in training. This thesis is the first to quantify the training demands in elite Rugby Union, therefore provides and novel and insightful findings for applied practitioners working in either the Premiership or the Championship.

9.3 Factors Affecting Match Injury Incidence: Key Performance Indicator and Playing Surface

The match (and training) demands are presented in section 9.2, demonstrating how the forwards complete greater amounts of actions relating to the contact elements of the match (tackles, ball carries, breakdown entries) whereas the backs complete greater amounts of distance and high-speed running distance. In chapter V, the influence of these match key performance indicators on match injury incidence was modelled. Furthermore, chapter VI explored the differences in match injury incidence between three types of commonly used playing surface (grass, hybrid and synthetic), all of which the players are exposed to over the course of a season. Overall match injury incidence was found to be 137.2 per 1000 h match exposure, therefore almost five times higher than the injury incidence reported in professional Football (Soccer) (27.5 per 1000 match h; Ekstrand et al., 2009). Therefore, exploring potential explanations behind the high match injury incidence in Rugby Union would allow applied practitioners with such knowledge to minimise, within reason, the likelihood of injury incidence; or at least better prepare the players for the exchanges they are likely to be exposed to during matches.

Chapter V demonstrated how the match key performance indicator variables (tackles, tackle assists, tackles missed, contact carries, breakdown entries and contact events) did not have an influence on match injury incidence. Models were produced with the response variables expressed in both an absolute and relative (to match duration for each individual player) terms. However, none of the variables returned a relationship with match injury incidence. It was hypothesised that this may be due to every aspect of Rugby Union requiring physical exertion; by its very nature the sport contains a high number of forceful contact events. This means that all players experience contact actions during a match and, thus, it is the exposure to any number of these contact actions, rather than the number of contact actions *per se*, that contributes to the high injury incidence seen in Rugby Union (Fuller et al., 2007b).

Whilst the key performance indicators did not affect match injury incidence, the likelihood of sustaining a match injury was found to be influenced by the type of playing surface on which the match took place. An artificial playing surface (hybrid or synthetic) approximately doubled the odds of sustaining a match injury (hybrid: OR = 2.58; synthetic: OR = 2.16; both compared to natural grass; Chapter VI). Playing surface also affected the incidence of both contact and non-contact injuries on the artificial playing surfaces, with the odds of sustaining a contact injury on hybrid or synthetic pitches more than double that on a natural grass surface (hybrid: OR = 2.31; synthetic: OR = 2.19). Furthermore, non-contact injury incidence was four times greater on the hybrid playing surface compared to natural grass (OR = 4.18). The inclusion of the hybrid playing surface in the present thesis extends the knowledge of previous work and given the hybrid surface elicited the highest injury rate (hybrid: 176.9 per 1000 h; synthetic: 160.3 per 1000 h; grass: 82.8 per 1000 h), it demonstrates an important finding. It has been hypothesised that the momentum kinetics, increased as a by-product of greater traction between the pitch and player footwear, acts as a contributor to the increased injury incidence associated with pitches with a synthetic component (Hendricks et al., 2014; Thomson et al., 2015).

To summarise, the hybrid and synthetic pitches yield a greater match injury incidence compared to grass. This is an important finding, and one that will interest applied practitioners. Both matches and training sessions commonly take place on hybrid and synthetic surfaces, therefore, having an understanding that a direct increase in the likelihood of injury incidence will occur may subsequently deter some coaches from unnecessarily exposing players to this increased risk. Match injury incidence was not explained by the match key performance indicator variables (Chapter V) and it was hypothesised that this may be due to the contact nature of Rugby Union and not, *per* se, the number of individual exposures. An alternative explanation is that a more important determinant of injury incidence in Rugby Union is the accumulation of load (i.e. the amount of exertion that a player applies during match play and/or training). Load measures such as sRPE load and GPS-derived variables (e.g.

distance and high-speed running distance), may therefore assist in explaining injury incidence in elite Rugby Union; this was further explored in chapters VII and VIII.

9.4 The Effect of Match and Training Load on the Incidence and Severity of Time-Loss Events

Chapters VII and VIII examined the influence of match and training load on the incidence and severity of time-loss events (injuries and illnesses). The main finding was that increases in match and training load result in not only an increased time-loss incidence, but also greater odds of the time-loss event being of major severity (i.e. ≥8 d lost). Chapter VII examined the influence of match and training load on the time-loss incidence. Results demonstrated how the absolute match and training load variables (absolute sRPE load, absolute distance and absolute high-speed running distance) best explained the variance in time-loss incidence. Furthermore, a unique aspect of the thesis was the quantification of load using the absolute, acute:chronic workload ratio and exponentially weighted moving average approaches. It was demonstrated in chapter VII that the exponentially weighted moving average method of load quantification better explained the likelihood of time-loss incidence compared to the more commonly used acute:chronic workload ratio approach. Additionally, players occupying forward positions were found to have a higher time-loss incidence rate compared to backs for all match and training load variables (ranging from 32 to 62%).

Figures 9.1 to 9.3 demonstrate a combination of chapters IV and VII, amalgamating the match and training demands of Rugby Union and the resultant time-loss incidence rates. Presenting the typical load exposure of the players (shown as the number of player days within each category) alongside the risk of time-loss incidence according to the load allows consideration of both the typical load the players are exposed to, and the resultant effect of this on time-loss incidence. This is ultimately what is of interest to applied practitioners (i.e. what is the time-loss incidence risk if a player is exposed to a certain load, and what happened as this load is increased/decreased?). For example, Figure 9.2A presents both the frequency of players being exposed to varying distances, alongside the time-loss incidence associated with each distance. As shown, the most commonly observed distance covered per training session/match was 3000 m, therefore, incidence rate of 0.011 time-loss incidences per player day for forwards and 0.007 time-loss incidence per player day for backs.

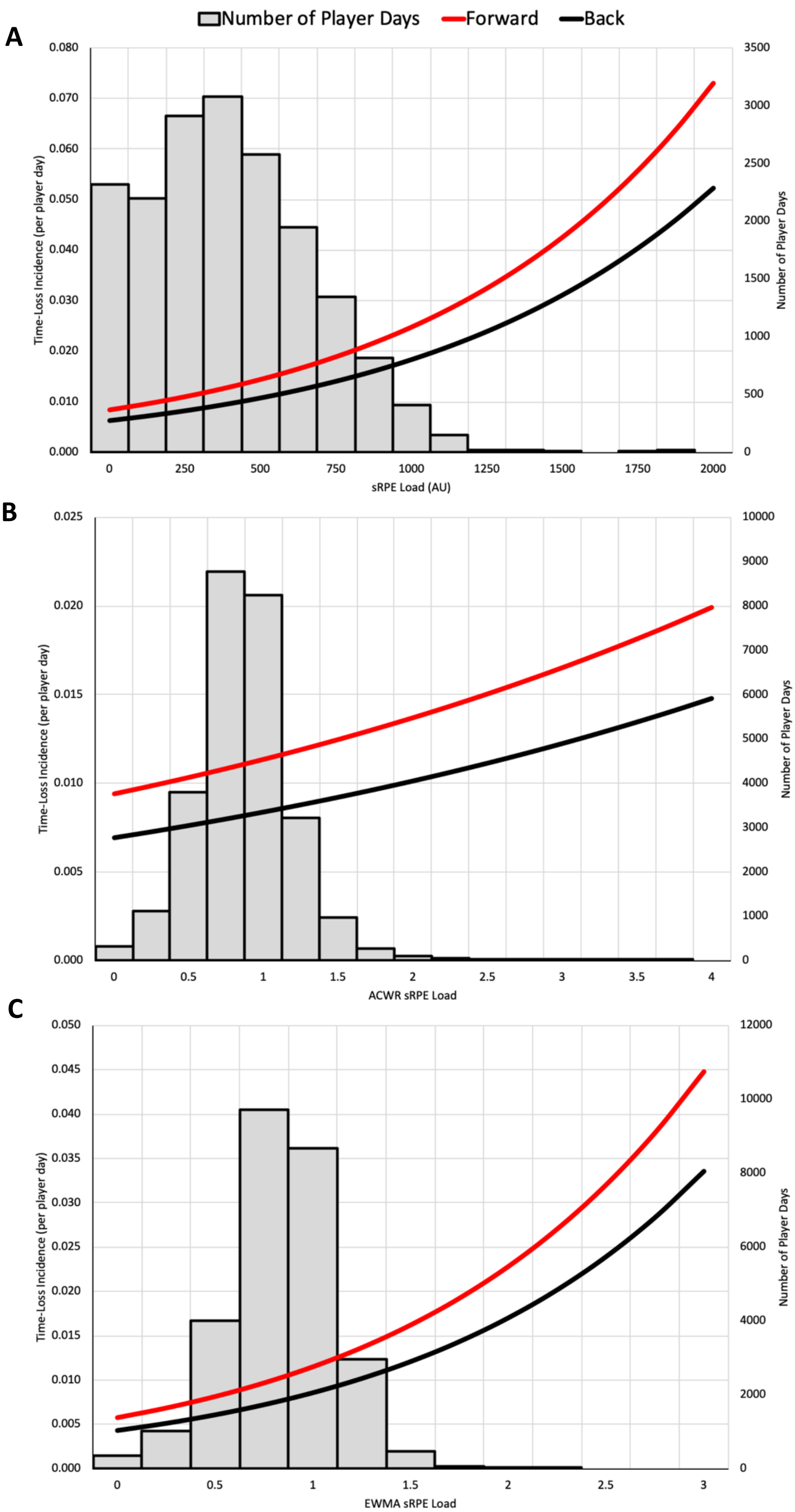


Figure 9.1. The relationship between time-loss incidence (per player day) in forwards (red line) and backs (black line) according to the absolute sRPE load **(9.1A)**, ACWR sRPE load **(9.1B)** and EWMA sRPE load **(9.1C)** variables; presented alongside the number of player days spent at each load (grey bars).

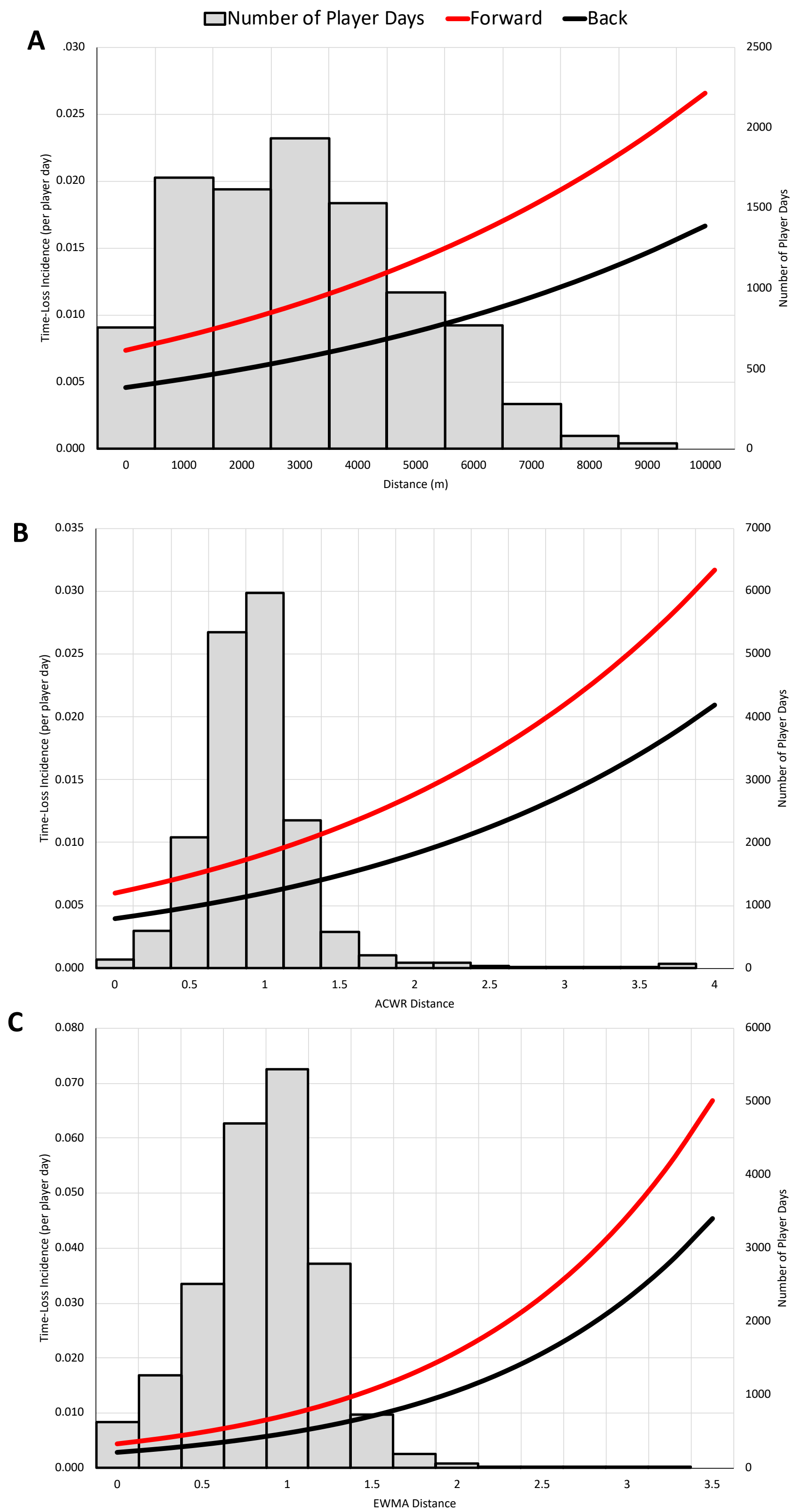


Figure 9.2. The relationship between time-loss incidence (per player day) in forwards (red line) and backs (black line) according to the absolute distance **(9.2A)**, ACWR distance **(9.2B)** and EWMA distance **(9.2C)** variables; presented alongside the number of player days spent at each load (grey bars).

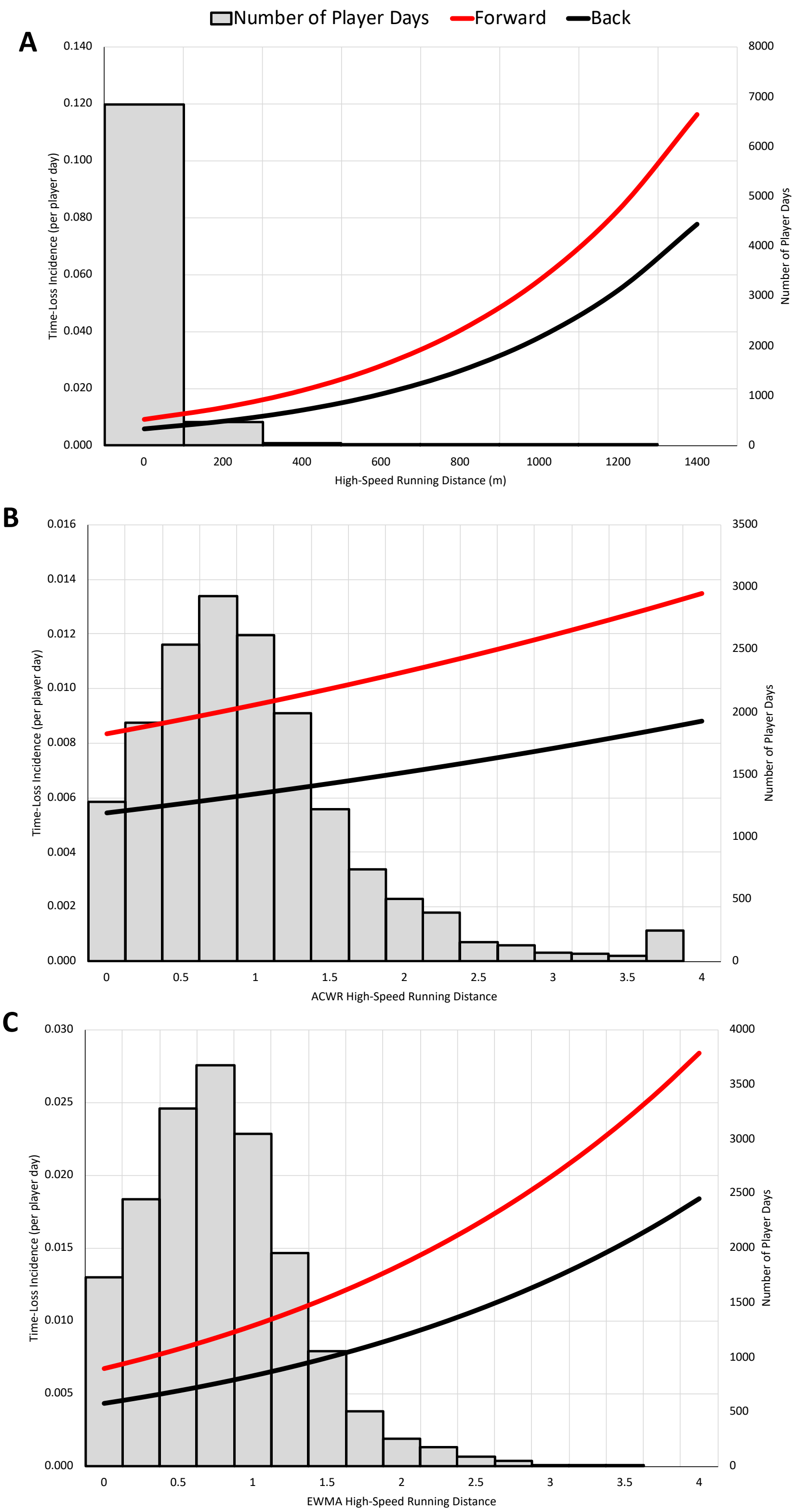


Figure 9.3. The relationship between time-loss incidence (per player day) in forwards (red line) and backs (black line) according to the absolute high-speed running distance **(9.3A)**, ACWR high-speed running distance **(9.3B)** and EWMA high-speed running distance **(9.3C)** variables; presented alongside the number of player days spent at each load (grey bars).

Figures 9.1, 9.2 and 9.3 are potentially of great utility to applied practitioners working in elite Rugby Union. Practitioners want to develop an understanding of how the load a player is exposed to affects subsequent time-loss incidence. The figures presented here allow this understanding to be developed alongside the common load seen during training sessions and matches in elite Rugby Union. Ultimately, coaches and support staff may choose to tactically periodise training depending upon the competition and opponent, in search of performance optimisation, in periods of the season where match outcome is of higher (or lesser) importance. By manipulating the match and training load of an individual or particular group of players, the likelihood of time-loss incidence can be balanced out against the performance improvements which could ultimately be achieved. The findings of this thesis will therefore allow practitioners to do this with an understanding of the subsequent effect on time-loss incidence.

The findings of this thesis also demonstrate how load affects not only time-loss incidence, but also the severity of the time-loss incidences that occur. When assessing the influence of match and training load on the severity of time-loss incidence (the likelihood of sustaining a major severity (≥8 d lost) compared to a minor severity (≤7 d lost) time-loss incidence), load quantified using the exponentially weighted moving average method of quantification explained more variance, when compared to both the absolute and acute:chronic workload ratio methods (Chapter VIII). This re-affirms the findings of chapter VII, where the exponentially weighted moving average approach was more sensitive to the variance in overall time-loss occurrence than the more commonly used acute:chronic workload ratio approach. Another finding that bridged both chapters (VII and VIII) was that sRPE load was the best measure of load, explaining more of the variance in both the incidence and severity of time-loss incidence, when compared to the GPS-derived distance and high-speed running variables. Unlike the GPS-derived variables, which require expensive technologies and software training to collect, sRPE load provides performance and medical staff with a low cost, easy to administer, method of match and training load assessment (Kraft et al., 2014). It is also possible that the sRPE variables provides a more accurate reflection of the contacts/collisions during Rugby Union (not picked up by GPS variables). Furthermore, sRPE also provides a measure of load for the gym-based sessions where GPS monitoring is not possible.

9.5 Practical Applications

The findings of this thesis will allow Rugby coaches and performance and medical staff working at elite Rugby Union clubs with a host of practical applications that they could implement as part of their training protocols and load management process. Firstly, the match demands, split by position (forward and back) and league of competition (Premiership and Championship) in chapter IV, provide the objective match demands which can subsequently inform training practices to ensure preparedness for match volume and intensity. Furthermore, the objective markers can also inform return to play protocols following injury, to ensure sufficient work is completed prior to reintegration and match selection availability. Furthermore, the equation in section 4.3.4, and the model characteristics in table 4.5 can provide the predicted number of tackles, contact carries, breakdown entries each position will complete for a set period of match duration. Again, providing objective markers to incorporate into training and rehabilitation protocols to ensure the specificity of training and adequate preparation of the players for the demands they will face in a match situation.

The second take home message for practitioners is the increased likelihood of sustaining a match injury on any playing surface that contains a synthetic element (i.e. hybrid or full synthetic). Despite this thesis exploring the association between pitch type and match injury in isolation, club training sessions frequently occur on artificial surfaces therefore the applicability of the increased 'risk' may also apply to training; this certainly warrants investigation in future research. Nonetheless, the association between playing surface and match injury incidence is clear; an important consideration for clubs and their support staff.

A crucial practical application highlighted in this thesis is the effectiveness of subjective sRPE load at explaining the variance in occurrence and severity of time-loss incidence. As previously mentioned, the ease at which sRPE can be collected across all levels of sport, let alone elite level Rugby Union, provides practitioners with the utility to assess match and training load in a low cost, efficient manner. The value of GPS should not be overlooked however. At elite level, GPS is commonly used by applied sport scientists. The ability of GPS to objectively quantify match and training demands, as demonstrated in chapter IV, is not possible through subjective sRPE load. Furthermore, the GPS-derived variables (distance and high-speed running distance) can also be incorporated into load management processes as shown in the findings of chapters VII and VIII. In similar vein to the equation which can be used to calculate key performance indicator demand, the equation in section 7.3.2.6, and the model charateristics in table 7.2, can provide the number of time-loss incidences per player day for load exposure, by position. Therefore, practitioners can calculate the increased likelihood of time-loss incidence should the training demand increase, for example.

The last main practical application that can be taken from the findings of this thesis is that the exponentially weighted moving average apporach to load quantification is more sensitive at explaining the variance in the occurrence and severity of time-loss incidence in elite Rugby Union players compared to the acute:chronic workload ratio approach. The acute:chronic workload ratio approach to load quantification and management has become seemingly common practice across elite sport following the exposure it gained on social media after its introduction. However, the concerns raised regarding its calculation methods as discussed in the review of literature (chapter II) coupled with the findings of experimental chapters VII and VIII, demonstrate how the exponentially weighted moving average approach to load quantification should be adopted when managing load from a long-term perspective; perhaps incorporated alongside the short-term, absolute daily load method. The load management processes of elite Rugby Union clubs should incorporate the absolute sRPE load, absolute distance and abolsute high-speed running distance measures when assessing the likelihood of time-loss incidence and the EWMA sRPE load and EWMA distance when assessing the probability of sustaining a major severity time-loss incidence (compared to a minor severity time-loss incidence).

9.6 Recommendations for Applied Practitioners

The studies presented within this thesis, and the practical applications presented in section 9.5, demonstrate how the findings could be utilised in an elite sporting environment. Through their role of Sport Scientist at the professional Rugby Union club, the candidate has applied a lot of the findings into their real-world practice to better inform the decision making processes of load management protocols, training session design and the playing surfaces on which training takes place. As such, the following recommendations for applied practitioners can be made, to ensure they best utilise the findings of this thesis:

- The use of sRPE load as a method of match and training should not be overlooked. All too often the use of sRPE load is percevied to be less informative than the more expensive, technologically advanced GPS-derived variables such as distance and high-speed running distance. However, the findings of this thesis demonstrate how the sRPE load measure of match and training load is more sensitive to the variance in the likelilhood of time-loss incidence occurrence and severity. sRPE load should therefore be incorporated into load management protocols in elite Rugby Union clubs by performance and medical staff to best inform practice and reduce the likelihood of time-loss incidence occurrence.

- For the long-term management of player match and training load, and for the ability to forecast a players load, the exponentially weighted moving average is superior to that of the acute:chronic workload ratio (which is the load quantification method commonly used throughtout elite sport). The findings of this thesis demonstrate how the exponentially weighted moving average load quantification method better explains the variance in both incidence and severity of time-loss incidence. Furthermore, when sRPE load was quantified using the exponentially weighted moving average method, it returned lower AIC and BIC compared to EWMA distance and EWMA high-speed running distance (as demonstrated in Tables 7.3 and 8.3). Another useful tool for practitioners to consider is the ability to forecast a players expected EWMA value by forecasting their predicted training / match exposures and then using the equations provided in experimental chapter VII to calculate the associated likelihood of time-loss incidence.

- The findings of Chapter VI present the increase in likelihood of match injury when the fixture takes place on a playing surface containing some artificial content (hybrid or synthetic). In the real-world it is not possible to move the location of a match should it be scheduled on either a hybrid or synthetic playing surface. However, it is commonplace for the training sessions in the preparation week prior to matches taking place on a synthetic surface, are undertaken on synthetic pitches if the club has access. It is therefore important for practitioners to consider the hypothesised increase in training injury likelihood given the increases in match injury likelihood on synthetic surfaces. From experience, minimising the number of training sessions taking place on synthetic surfaces to essential sessions only (i.e. the final session of the training week) will alleviate some of the elevated injury likelihood when exposing players to pitches that are either hybrid or synthetic.

9.7 Limitations

The main limitations of the present thesis were the restriction of data collection to only a single professional Rugby Union club and the misfortune of relegation from the Premiership to the Championship at the end of the first season of data collection. Whilst this provided the unique opportunity to compare the two leagues of competition, it could be argued that the compeitiveness of the Championship for a club with “Premiership status” is minimal, and therefore the applicability of the findings to all clubs within the Championship is impractical, given the semi-professional status of some competing teams. Given that the data collection for the studies presented in this thesis was limited to a single professional Rugby Union club, the applicability of the findings across clubs is unknown. However, from personal experience, the programme design and the physical profiles of the players are very similar between clubs, and consequently the findings of this thesis can be applied, with appropriate caution, across elite Rugby Union clubs.

9.8 Conclusions

Overall the findings from this thesis provide novel evidence regarding the match and training load demands of elite Rugby Union and how these demands relate to time-loss incidence risk. Specifically:

- *The match and training demands are dependent upon position*: The running demands were higher in both training and matches for the backs whereas the contact actions of matches were higher in the forwards (Chapter IV).

- *The demands of the Premiership and Championship were opposing*: The demand of high-speed running distance and defensive actions (number of tackles) is greater in the Premiership, whereas the attacking actions (contact carries and breakdown entries) were greater in the Championship (Chapter IV).

- *Key performance indicators did not affect injury incidence in matches*: The number of tackles, tackle assists, contact carries, breakdown entries and contact events did not influence the likelihood of sustaining a match injury (Chapter V).

- *Synthetic pitches increase injury incidence in matches*: The odds of sustaining a match injury are doubled on pitches containing any synthetic content (hybrid or synthetic playing surfaces), compared to natural grass (Chapter VI).

- *Higher levels of match and training load increase the occurrence and severity of time-loss incidence*: The relationship between match and training load and the occurrence and severity of time-loss incidence is positive. Increased levels of match and training load is associated with an amplified likelihood of both sustaining a time-loss incidence and an increased likelihood that the time-loss incidence will be of greater severity (Chapter VII).

- *sRPE load appears to explain more of the variance in time-loss incidence and severity than GPS-derived variables*: Subjective sRPE load returned lower AIC and BIC values in the model characteristics of chapters VII and VIII, therefore suggesting sRPE load is more sensitive to the variance in the likelihood of sustaining, and the severity of, a time-loss incidence, when compared to distance and high-speed running distance.

- *The exponentially weighted moving average and absolute approaches to load quantification are better indicators of the change in time-loss incidence risk and severity than the acute:chronic workload ratio approach*: The model characteristics (AIC and BIC) of chapters VII and VIII demonstrate the how the ability of the exponentially weighted moving average and absolute methods of load quantification are superior to that of the acute:chronic workload ratio and should therefore be incorporated in load management protocols of elite Rugby Union clubs.

9.9 Recommendations for Future Research

To continue to advance knowledge and practical application of research examining the demands, actions, load and time-loss incidence in elite Rugby Union, the following suggestions are recommended for future research:

- Given the effectiveness of GPS-derived variables in quantifying the demands of match play, the increase in the number of variables studied may provide greater resolution as to the specific match demands. By providing greater clarity between the distance covered at varying percentages of an individual players maximum velocity, the accuracy of rehabilitation and match specific training drills can be enhanced.

- Coupled with the increase in variables, the expansion of positional groups, from forwards and backs, to prop, hooker, second row, back row, scrum-half, fly-half, centre and back 3 would add greater precision; but would also require a larger dataset (i.e. from multiple clubs across a number of seasons of competition).

- Given the sport of Rugby Union requires a significant amount of acceleration and deceleration, variables assessing these demands may provide a useful insight into time-loss incidence and severity.

- To investigate the influence of synthetic surfaces on training injuries and given the number of different pitch types in the professional game (grass, hybrid, synthetic), relationships between the switching of surfaces from week-to-week depending upon the venue of match/competition could also be considered.

- Finally, to continue to develop an understanding of the variance in occurrence and severity of time-loss incidence in matches and training, the inclusion of additional GPS-derived variables, like those suggested above, may provide an additional insight to inform load management protocols of elite sport.

In all future studies it remains important to assess the comprehensive number of variables associated with Rugby Union training and matches alongside the demands, actions, load and time-loss incidence using complex statistical models as outlined in this thesis. By providing the associated odds and equations, it supplies applied practitioners with the utility to manage load and make informed decisions on the training and rehabilitation processes with enhanced accuracy.

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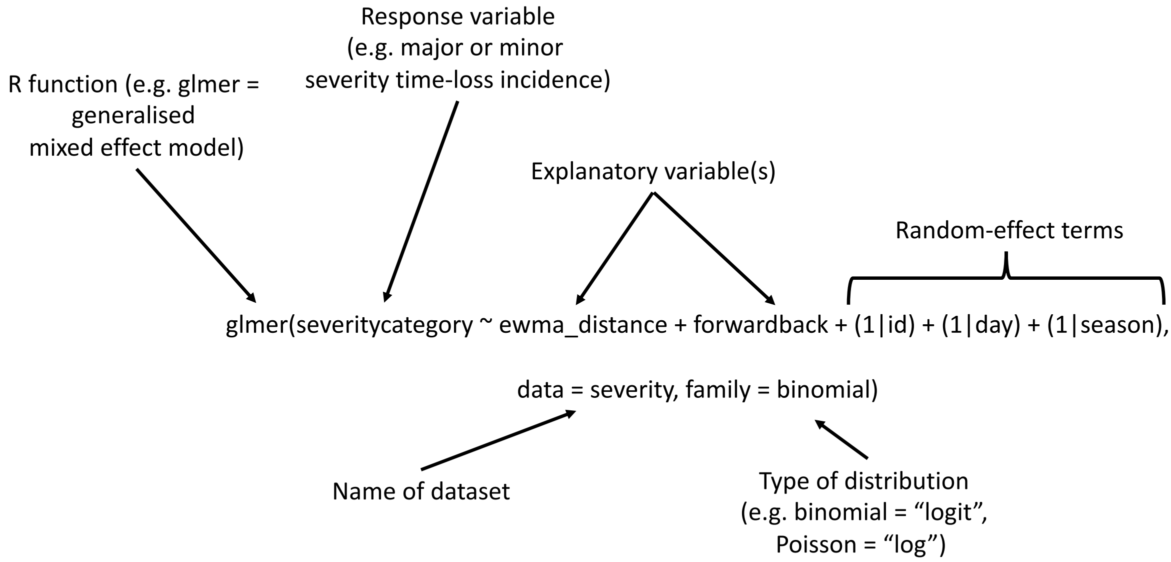
List of Appendices

Appendix A: Example R-scripts.

Worked Example



Chapter IV – Demands

For continuous response variables:

For training data:

lme(distance ~ forwardback, random = ~1|id, data = TrainDes)

For match data:

lme(distance ~ forwardback + match_duration, random = ~1|id, data = MatchDes)

For count response variables:

With Poisson distribution:

glmer(ind_tackles_missed ~ forwardback + match_duration + (1|id), data = MatchDes, family = poisson)

With negative binomial distribution:

glmer.nb(ind_tackles_attempted ~ forwardback + match_duration + (1|id), data = MatchDes)

Chapter V – Match Injury

```
glmer(injury ~ ind_tackles_attempted + (1|id) + (1|match_number) + (1|season), data = MatchKPI, family = binomial)
```

Chapter VI – Playing Surface

```
glmer(injury ~ pitch_type + (1|id) + (1|match_number) + (1|season), data = MatchKPI, family = binomial)
```

With playing surface as a factor (i.e. to allow comparisons between individual surfaces):

```
MatchKPI$pitch_typef = as.factor(MatchKPI$pitch_type)
```

```
glmer(injury ~ pitch_typef + (1|id) + (1|match_number) + (1|season), data = MatchKPI, family = binomial)
```

Chapter VII – Load

```
glmer(injury ~ acwr_distance + forwardback + age + (1|id) + (1|day) + (1|season), data = season12, family = binomial)
```

Chapter VIII – Severity

```
glmer(severitycategory ~ ewma_distance + forwardback + (1|id) + (1|day) + (1|season), data = severity, family = binomial)
```

Appendix B: Modified Borg CR-10 Rating of Perceived Exertion (RPE) Scale (Borg et al., 1987).

RPE (Rating of Perceived Exertion).	
Rating.	**Description.**
0	Nothing At All.
1	Very Light.
2	Fairly Light.
3	Moderate.
4	Somewhat Hard.
5	Hard.
6	
7	Very Hard.
8	
9	
10	Very, Very Hard (Maximal).

The modified Borg CR-10 rating of perceived exertion (RPE) scale.