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Player Load Monitoring and Injury Risk in Elite Scottish Rugby Union

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Player Load Monitoring and Injury Risk in Elite Scottish Rugby Union

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Declaration of the submitted work

The work presented in this thesis has not been submitted for any other degree or professional qualification.

*Student's Signature*_____[redacted]________

Declaration of authorship

I state that this thesis is the result of my own independent work, completed by myself personally, and I am the author of this thesis.

*Student's Signature*____ [redacted]___________

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PUBLICATIONS AND PRESENTATIONS

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Paul, C., Campbell, T.G., Yule, S., Walsh, J., & Palmer, D. (2021). The influence of training volume on training and match injury risk in elite Scottish rugby union players - [1665]. *IOC World Conference on Prevention of Injury & Illness in Sport*, *Monaco*. Accepted **(see APPENDIX D for abstract).**

ABSTRACT

There is a limited amount of research in professional Rugby Union to minimise the high injury risk associated with the sport. Given that injuries are sustained when workload is performed, the monitoring of player loads, and how these loads may relate to injury is of importance. This thesis presents an investigation of various external workloads and how these workloads may influence injury risk. Firstly, training volume and match exposure data were assessed. Players with the highest mean weekly training volume had the lowest injury incidence and injury burden rates. On the contrary, players with very high 1- and 2-weekly training volumes were significantly more likely to be injured compared to their respective reference groups. For match exposure data, injury incidence and injury burden rates were lowest for players involved in ≥ 25 matches per season. For training volume, the odds of injury increased linearly as the ACWR increased > 1.00. This thesis also investigated pitch-based workloads via global positioning system devices housing inertial measurement units. Derived measures of 1 – 4 weekly loads, weekly changes in load and ACWR data were used to investigate workload-injury relationships. Large difference in the workloads completed by positional groups were reported, which also translated to position-specific injury risks. It was concluded that there is a need for a more individualised monitoring approach when measuring workload-injury relationships for pitch-based loads. Rugby Union match play contact loads were also investigated in this thesis. Using video coding analysis, large differences between positional groups for contact volume and the number of contact events engaged in per player per match were reported. Ball Carrying events reported the highest injury risk per event (79.8 events per injury). In particular, velocity, tackle type and impact force were areas of concern. The multiple workload measures adopted in this thesis to investigate the influence of external workload on injury risk highlight that the workload-injury picture can greatly differ depending on the workload metrics adopted to monitor load in professional Rugby Union.

CHAPTER 1: INTRODUCTION

1.1 RESEARCH OVERVIEW

It is thought that Rugby Union was born in 1823 when William Webb Ellis disregarded the rules of Football entirely by picking up the ball and running towards the opposition's goal, which ultimately became one of the most distinctive features of the game (Dunning and Sheard, 2005). During this time the rules of Rugby Union (then known as Football, as this was yet to be split into various codes) were often decided prior to match play, and were not officially formed until 1845. The first international Rugby Union match was played in 1871, when Scotland beat England 1-0 at Raeburn Place. Two years later the Scottish Rugby Union (SRU) was founded. Despite the relatively long history of the sport, Rugby Union did not gain professionalism until 1995.

The modern game of Rugby Union is played over two, 40-minute periods with fifteen players from each team starting on the field. The 'Forwards' represent numbers 1-8, whereas the 'Backs' represent numbers 9-15 (See Figure 1.1). During match play, Rugby Union teams are allowed eight substitutions, and can make provisional replacements for injuries requiring medical treatment (i.e., blood substitutions).

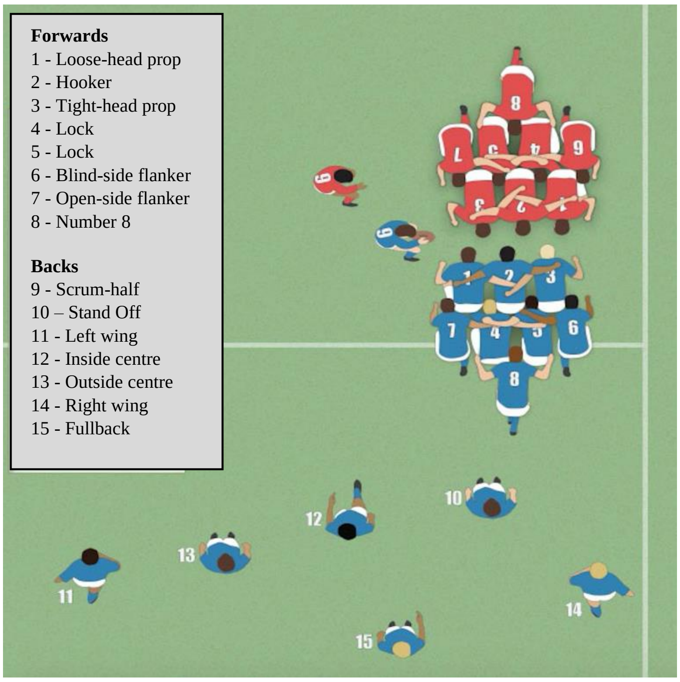


Figure 1.1: Rugby Union positions from a scrum formation (modified from Palenski. [2016]).

Rugby Union is a physically demanding intermittent collision sport, which requires players of all positions to engage in repeated bouts of high intensity exercise interspersed with periods of low intensity activity (Roberts *et al*., 2008; Williams *et al.*, 2013). Periods of high-intensity exercise can consist of high-speed running, sprinting, tackling, rucking, mauling and set piece scrummaging and lineouts; periods of low intensity activity consist of standing, walking and jogging (Duthie *et al.*, 2003; Roberts *et al*., 2008; Williams *et al*., 2013). Unsurprisingly, it has been reported that the incidence of injury in professional Rugby Union is one of the highest in professional team sport (Williams *et al.*, 2013). This is thought to have coincided with the advent of professionalism, and consequently full time training (Garraway *et al.*, 2000).

With the occurrence of professionalism in 1995, players have been expected to adapt to the increased nature of the game, and show the physical attributes associated with full time athletes (Garraway *et al.*, 2000). As such, the excessive training and match demands placed on professional players are considered to be one of the greatest risk factors for injury in Rugby Union. Minimising injury risk in professional Rugby Union is important for both the short and long-term player welfare issues associated with the sport. For instance, following a training or match injury, exclusion from training practices and match play may be necessary to allow for recovery. In turn, this will have a negative impact on performance outcomes, and may also have a psychological impact from exclusion and a lack of social engagement with team mates. Furthermore, Rugby Union players have been reported to have long-term repercussions from injuries sustained during their careers, such as more joint replacements, osteoarthritis, anxiety and significant motor and cognitive deficiencies in later life compared to non-contact age-matched peers (Davies *et al.*, 2017; Hume *et al.*, 2017; Pearce *et al.*, 2018). Consequently, these long-term effects may also influence employment opportunities and related earnings, as well as medical costs to overcome these ongoing issues.

The risk of sustaining an injury during Rugby Union training or match play is often a consequence of the external load dose. Numerous studies have reported negative associations with very high and/or very low workloads (Bowen *et al.*, 2020; Colby *et al.*, 2014; Cross *et al.*, 2016; Gabbett, 2016a; Gabbett *et al.*, 2016a; Hulin *et al.*, 2016a; Malone *et al.*, 2016; Malone *et al.*, 2017c; Murray *et al.*, 2017b; Rogalski *et al.*, 2013), whereas other studies have shown that appropriate 'intermediate' workloads can reduce injury risk (Andrade *et al*., 2020; Bowen *et al.*, 2020; Brooks *et al*., 2008; Cross *et al.*, 2016). A common finding between these studies is that an appropriate training (or match) dose is likely to develop well-conditioned athletes that are resilient to the high loads associated with professional Rugby Union. As such, the advent of professionalism and the concurrent increase in injury risk may not have been the result of improved performance and the development of physical characteristics, but simply that players were not appropriately trained and conditioned to cope with the demands of full time training and competitive match play.

Given that training load has been linked to both an increase and decrease in injury risk, it is important for coaches and practitioners to develop effective training methods that improve player performance whilst concurrently allowing for appropriate rest and recovery to reduce injury risk. It has been reported that training accounts for 89-95% of total exercise exposure, whereas matches account for 5-11% throughout a given season (Kemp *et al*., 2016; Fuller *et al*., 2008). With this in mind, a particular focus for coaches is to implement well-structured training programmes that induce effective adaptations of the cardiovascular, aerobic and muscular systems (Vanrenterghem *et al.,* 2017). In order to achieve these positive adaptations, coaches need to adequately monitor training variables and appropriately balance work-to-rest ratios (Banister, 1991; Smith, 2003). Recently, training and match workload have been identified as two factors that may play critical roles on player injury risk and performance. The terms 'Workload' and 'load' are used widely in Rugby Union to define both the external stress applied to an individual and/or define an individual's internal physiological and psychological responses to that external stress (Quarrie *et al.*, 2016). Thus, workload can be defined as: 'the total stressors and demands applied to the players' (Quarrie *et al.*, 2016), and can be characterised by the FITT acronym—frequency, intensity, time and type (Quarrie *et al.*, 2016). Exposing players to appropriate workloads that consider these aspects of player load can aid in promoting exercise-induced adaptations without inappropriately inducing fatigue and consequently, increasing injury risk. This is a challenging task for coaches and requires careful consideration when planning, implementing and adapting external workload.

The external workload that an athlete is exposed to can be easily modified and altered for any individual within any position in professional Rugby Union. Therefore, appropriate adaptation of external load can minimise player fatigue and injury risk (Brooks *et al.*, 2008; Hulin *et al.*, 2014, 2016a; Cross e*t al.*, 2016; Gabbett *et al.*, 2016a; Williams *et al.*, 2017b). In turn, this will aid in the promotion of training-induced adaptations and successful performance. Whether exposure to external load results in positive adaptations or negative deteriorations however, largely depend on the structure and function of the training programme (Comyns and Flanagan, 2013), and the overall load that player is placed under, including match load.

External load in Rugby Union has been quantified using a number of training and match load measures. Player training hours (training volume) over a given week, month, seasonal split (e.g., pre-season vs. in-seasons) or between seasons have previously been shown to be an important risk factor in Rugby Union (Brooks *et al.*, 2006b, 2008; West *et al.*, 2019). For example, Brooks *et al.* (2006b), reported that increased training volume the week before match play was associated with greater hamstring injury rates, particularly for major severity injuries. In addition, both Brooks *et al*. (2005b) and West *et al*. (2019), reported player injury incidence was at its lowest for gym-based conditioning (0.7 and 0.9 injuries per 1000 player-training hours, respectively), and that injury incidence was greater for on-pitch work in comparison.

Beyond measuring the risk factors of training volume, the number of games played (match exposure) over 12-month periods (a season) or monthly periods (30-day match involvements) have previously been linked to injury risk in Rugby Union (Williams *et al.*, 2017b). Williams *et al.* (2017b), previously reported that players who were involved in less than 15 matches over a season were more likely to be injured. It is likely that players involved in less than 15 matches over a season lack match robustness, and cannot cope with the collision events associated with the sport. On the other hand, authors also reported an increased injury risk for players involved in more than 35 matches over a season. This may be a result of chronic match fatigue, resulting in a reduction in the stress-bearing capacity of soft tissue, thereby also increasing injury risk. Williams *et al.* (2017b), reported that monthly match exposure was linearly associated with injury risk, suggesting that acute increases in match exposure are positively associated with a higher injury risk.

Although the influence of volume and exposure on injury risk have provided an important insight into the methods that can be adopted to minimise injury risk in Rugby Union, there are limitations with these approaches. Neither of these loading measures can quantify the intensity of the given training session or match, meaning variations in the workload performed each day cannot be accounted for. Furthermore, positional differences, in terms of the unique loads each player is subjected to during training and/or match play, and how these different workloads may relate to injury cannot be monitored or better understood unless an intensity measure is included in the monitoring process.

Global positioning system (GPS) devices housing inertial measurement unit technology (IMU) are one of the most commonly used monitoring tools to quantify the intensity of Rugby Union training and match pitch-based workloads. Numerous studies that have previously used these devices have shown that positional differences in Rugby Union are considerable (Cunniffe *et al*., 2009; Cunningham *et al.*, 2018; Howe *et al.*, 2017; Lindsay *et al.*, 2015; Pollard *et al.*, 2018; Reardon *et al.*, 2017b). These studies highlight that a ‘one size fits all’ approach to monitoring training and match loads may be sub-optimal due to the notable differences in position-specific roles, technical competency and anthropometry between players (McLaren *et al.*, 2016). For instance, it is well documented that Forwards engage in more contact events (Duthie *et al*., 2003; Suarez-Arrones *et al*., 2014; Roberts *et al.*, 2008), whereas Backs cover greater distances at higher running velocities during match play (Cunniffe *et al.*, 2009; Dubois *et al.*, 2017; Lindsay *et al.*, 2015; Pollard *et al.*, 2018; Reardon *et al.*, 2017b). Variations in the physical attributes and position-specific roles of players within a team means that individuals will experience different training intensities/loads within the same session (Hoff *et al.,* 2002; Lovell *et al.*, 2013; Tee *et al.,* 2015). This means that the ability of coaches to appropriately plan and effectively structure training plans that elicit optimal exercise-induced adaptations, and adequately prepare players across all positions for their relative match demands is consequently implausible if they are adopting a ‘one-size fits all approach’ (Soligard *et al.*, 2016; Tee *et al.*, 2015).

In load-monitoring studies, incorporating derivative measures from the workload data collected can help inform injury risk (Williams *et al*., 2017a). For instance, practitioners can analyse daily loads, weekly loads, week-to-week changes in load, cumulative loads and/or various forms of acute: chronic workload ratios (ACWRs). All of which have been associated with injury risk in contact team sports (Comyns and Flanagan, 2013; Cross *et al*., 2016; Hulin *et al*., 2016a, 2016b; Williams *et al*., 2017a; Windt and Gabbett, 2016). To the author’s knowledge, these have only been investigated in Rugby Union via the Session Rating of Perceived Exertion (sRPE) method (Cross *et al*., 2016). On the other hand, other contact team sports have used a number of GPS and IMU metrics to investigate associations between workload risk factors and injury risk. For example, Murray *et al.* (2017c), reported that elite Australian Football players with high 1 weekly loads above 2500 arbitrary units (AU) for PlayerLoad^{TM} were significantly more likely to sustain an injury. Contrary to high 1-weekly loads however, Cummins *et al.* (2019), reported that Rugby League players with high 4-week PlayerLoad^{TM} (>3800 AU) had a reduced injury-risk. These findings suggest that when players are exposed to high workloads over acute time frames (e.g., 1-weekly periods), injury risk may be increased. On the other hand, acquiring higher loads over chronic timeframes (e.g., 4-weekly periods) may reduce injury risk. Beyond individually assessing acute or chronic periods, the use of ACWRs in elite contact team sports is now well documented for informing workload-injury relationships. Importantly, there are a number of methods that can be used to calculate ACWRs for injury risk analysis. For instance, authors have used coupled/uncoupled rolling averages or exponentially weighted moving averages (EWMAs) over daily and weekly timeframes (Impellizzeri *et al.*, 2019; Lolli *et al.*, 2017, 2019; Menaspà, 2017; Williams *et al*., 2016; Windt & Gabbett, 2018). The utility and methodological recommendations associated with these measures are explored later in this thesis.

Although GPS devices are highly practical for monitoring player loads during training and match play environments due to ease of data collection, it has to be noted that Rugby Union is a contact sport, and success in contact sports is largely influenced by a player's ability to tackle and win the tackle contest (Gabbett, 2016a). Previously, it has been reported that both the number of tackles a player engages in and the magnitude of tackle impacts sustained can increase the physical demands of match play in Rugby Union (Hendricks & Lambert. 2014). With this in mind, understanding how these contact events influence physical performance and fatigue is important for optimising player performance and reducing injury risk. Exercise-induced fatigue has been shown to deteriorate tackling technique and tackle success, thus increasing the likelihood of injury during periods of intense match play (Gabbett, 2016a). Developing a better understanding of how these contact events influence the positional demands of Rugby Union matches is consequently vital. Previous research has used video coding analysis methods to quantify these demands and further understand how contact events (e.g., tackling, rucking, mauling and scrummaging) may influence injury risk in professional Rugby Union players (Fuller *et al.*, 2007a; Fuller *et al.*, 2010; Reardon *et al.*, 2017a). Noteworthy, is that this can also be achieved via IMU technology, but the utility of these devices to accurately identify contact events has been questioned (Reardon *et al.*, 2017a). In fact, video coding analysis is often used as the reference criteria to investigate how accurate IMUs are for detecting these events (Gabbett, 2013; Reardon *et al.*, 2017a). Therefore, as it currently stands, video coding analysis is the gold standard for identifying and collecting workload data on the contact aspects of Rugby Union match play. This method provides important information that cannot to be acquired via more 'technologically advanced' practices.

From the use of simple and practical methods of measuring external load, such as volume and/or exposure of exercise, to more advanced technological methods such as GPS and IMU derived loads and video coding methods, injury risk has been identified and evaluated in a number of contact team sports. Many of these studies have involved professional Rugby Union cohorts, but these findings cannot be generalised to all professional organisations. In addition, the lack of research in some areas of Rugby Union, such as the incorporation of GPS and IMU derived measures with loading calculations needs addressed. This thesis will provide an overview of the training and match associated risk factors for injury in elite Scottish Rugby Union, and where appropriate, risk factors that have been identified in other contact team sports. From the evidence-based findings of previous work, this thesis will develop a number of important research questions, aims and objectives that will assist in providing practical applications and guidance for practitioners and coaches aiming to improve player performance and welfare in professional Rugby Union.

1.2 AIMS OF THESIS

Aim 1 (Chapter 3): to investigate the influence of training and match volume (hours) and exposure (numbers of competitive games played) on training and match injury risk in elite Scottish Rugby Union.

Aim 2 (Chapter 4B): to investigate the relationship between GPS/IMU workloads during Rugby Union pitch based training and competitive match play and injury risk in Scottish elite Rugby Union players.

Aim 3 (Chapter 5): to investigate the demands and injury risk associated with contact events in professional Scottish Rugby Union matches.

1.3 RESEARCH QUESTIONS

Research Question 1 (Chapter 3): How does training and match volume and exposure influence injury risk in elite Scottish Rugby Union players?

Research Question 2 (Chapter 4A): Can two different GPS devices from different manufacturers reliably measure the total distance covered by Rugby Union players during pitch-based training?

Research Question 3 (Chapter 3 and 4B): What load measures (i.e., daily loads, cumulative loads, weekly changes in load and ACWR calculated loads) are best for informing injury risk in elite Rugby Union, from both a volume (hours) and workload (GPS and IMU derived measures) perspective?

Research Question 4 (Chapter 5): What are the contact demands and injury risk of elite Scottish Rugby Union, and how does this data compare to other well established load monitoring practices?

1.4 STRUCTURE OF THESIS

Chapter 2: Literature Review

This chapter provides an overall rationale for the research conducted in this thesis by building upon that of early principles and theoretical models that have, over time, provided sports scientists, coaches and practitioners with the tools needed to adequately and accurately monitor the workloads associated with professional Rugby Union players today. Through contemporary methods for tracking workloads and investigating the resulting injury risk associated with these workload patterns, this chapter has used key literature within the area of modifiable workload monitoring and injury risk analysis in professional Rugby Union and, where applicable, from other contact team sports. This chapter highlights the importance of training periodisation and external workload modification to alter the exercising dose within a periodised programme, which ultimately, can optimise performance and injury risk. The experimental areas investigated were: (1) volume and exposure, (2) training and match intensity, and (3) the contact demands of Rugby Union match play.

Chapter 3: Understanding the Match and Training Volume-Injury Relationship in Elite Scottish Rugby Union

The purpose of this chapter was to investigate the influence of training and match volume (hours) and exposure (numbers of competitive games played) on training and match injury risk in elite Scottish Rugby Union. This was achieved by providing incidence, severity and burden values across the two seasons of data collection, as well as investigating mean weekly training volume similar to that of previous Rugby Union research. This chapter also provides further research on 12-month and 1-month match exposure data. The association between training volume and injury risk in professional Scottish Rugby Union players and how this relationship is moderated by cumulative volume, weekly changes in volume, and various acute: chronic workload ratios - which have previously been recommended - were investigated.

Chapter 4A: The Interunit Reliability of Two 10-Hz Global Positioning System Devices to Report Total Distance during Rugby Union Pitch-Based Training

Within Scottish Rugby Union, different GPS devices housing IMUs are used between teams. Therefore, Chapter 4A aimed to compare two of the most commonly used and commercially available GPS units (Catapult Optimeye S5 and GPSports EVO 10 Hz devices) for measuring total distance data during Rugby Union on-pitch work. This study was conducted prior to Chapter 4B given that comparing or combining data across teams would not have been possible if the devices reported unreliable results. Therefore, the researcher investigated the interunit reliability of these devices to ensure the data collected in chapter 4B (for total distance over two seasons) was reliable, and that the findings reported were valid.

Chapter 4B: Quantifying the On-Pitch Demands of Elite Scottish Rugby Union Training and Match Play and its Association with Injury Risk

This chapter aims to investigate the relationship between on-pitch training and match play workload data (measured via GPS devices housing IMU technology), and its influence on injury risk. Similar to Chapter 3, this Chapter investigates the association between training and match workload intensity data and injury risk via cumulative loads, weekly changes in load, and the acute: chronic workload ratio. In addition, given the positional differences previously reported in the literature for studies using GPS and IMU data, this Chapter analysed workload-injury relationships in two ways. Firstly, a team analysis was conducted (all players combined for analysis), and secondly, players were split into positional groups (see Supplementary Data in Appendix F). This allowed position-specific workloads and their association with injury risk to be explored.

Chapter 5: Quantifying the Injury Risk of Contact Events in Professional Rugby Union

This chapter aims to investigate the contact load and injury risk of professional Scottish Rugby Union. Section A of this chapter focused on both contact volume (duration of time players were exposed to contact per match) and contact events (number of contact events engaged in per match). These workload metrics were also investigated in relation to game quarter and pitch location. Given the positional differences previously presented in the literature, contact load and injury risk were assessed via positional groups where possible. The relative risk of injury for various pre-tackle and tackle-phase contact characteristics for Ball Carrying was investigated based on previous findings in the literature and the data presented in this study. Section B of this study presented workload and injury data using a variety of different methods adopted in this thesis to monitor load and investigate injury risk. In addition, Section B provided new measures that may be helpful for tracking load and injury risk in Rugby Union.

Chapter 6: General Discussion and Conclusions

This chapter presents an overview of the key findings from each study, and reinforces some of the key outcomes of this thesis. This chapter also presents a number of avenues in which the research from this thesis has contributed to the existing literature for workload monitoring and injury risk analysis. Considerations of the methodological approaches adopted across each study is given, highlighting the strengths and weaknesses of each. How the outcomes of this thesis apply to practical and research settings is considered and presented based from the research conducted. In line with this, considerations for load monitoring practices are discussed, based on earlier efforts to monitor load/injury risk. From this novel work, directions of potential future research are discussed and suggested, and final conclusions of the thesis are drawn.

CHAPTER 2: REVIEW OF LITERATURE

"*The differences between expert performers and normal adults are not immutable, that is, due to genetically prescribed talent. Instead, these differences reflect a life-long period of deliberate effort to improve performance*" **Anders Ericsson**

2.1 THE MONITORING OF PLAYER LOAD

2.1.1 From Past to Present – A Brief Historical Overview

The grand tale of Milo, a 6th-century BC Italian farm boy born in the city of Crotona, Italy, would become known for being the world's strongest man (Foster *et al.*, 2017). An ancient Olympian wrestling legend whose story embodies a large proportion of what contemporary sports science preaches today, is famous in the strength and conditioning circle. He is best known for carrying a growing bullock every day until he was able to carry a full-sized, half-tonne bull on his shoulders (Edgley, 2018). His simple tale epitomises the law of progressive overloading, such that, as the bull grew in size, so did Milo and his strength (Edgley, 2018). This easily understood philosophy of how athletes can respond to workloads, characterises the contemporary concept of progressive overload and the performance outcomes that result from an appropriate exercise dose over time (Foster *et al.*, 2017).

Even back in the ancient Olympics athletes had a basic understanding of specialisation for their chosen event, progressive overload and the fundamental practises needed to stimulate muscle adaptation for improved strength, speed, power and ultimately, greater performance (Bourne, 2008). For example, athletes would complete vigorous activities such as picking up heavy loads, hacking, digging, breaking from wrestling grapples (strength), performing various running drills, shadow boxing, sparring with opponents (speed), hurling the discus or jumping continuously without rest (power), to name a few (Bourne, 2008). Together these exercises would be categorised as general preparation or "fatigue work" (Bourne, 2008), which follows a similar concept utilised today, a previous secret of the Soviet Union, known as 'General Physical Preparedness' (Edgley, 2018). Its simplicity verges on the primitive, and its concept can be characterised by being general in your foundations so you can be specific in your goals (Edgley, 2018).

Essentially, this is a non-specific form of training that encourages the use of compound functional movements that recruit universal motor patterns and develop a high work capacity (the amount of training that can be completed, recovered from and adapted to) whilst improving strength, speed, flexibility, endurance and skill – all of which professional Rugby Union players need to excel in their sport. It is arguably simple, but absolutely necessary to improve mobility and movement quality, and enhance the body's ability to tolerate greater workloads and prevent muscular imbalances (Edgley, 2018).

Athletes understood this even in the ancient times, and importantly, also understood the significance and necessity for rest and recovery (Bourne, 2008). Nevertheless, sometime after, the methods used to optimise performance began to shift, especially as technology improved. For example, two Finnish Olympians in Scandinavia named Hannes Kolehmainen and Paavo Nurmi were often seen using stopwatches while running track. Although forgotten in the pages of history as to whether these were used for race pacing, tracking progression or timing rest intervals (Foster *et al.*, 2017), they provide early evidence of athlete perceptions on the utility of load monitoring. This value of training was further progressed by Gösta Holmér, who later created the concept of "fartlek" training (Foster *et al.*, 2017); a high-intensity interval method that had various intensity segments. Fartlek training provided athletes with a workout that was lower in volume but greater in intensity than traditional steady state exercise. This was particularly important as these athletes were not paid for their commitments, and therefore had to work hard labour throughout the day (Foster *et al.*, 2017). Therefore, fartlek training provided early evidence that performance and well-being could be improved simply by adapting the intensity and volume of exercise.

A limitation of these early training methods however, was the difficulty in quantifying how this type of training was aiding in performance improvements. As such, interval training was developed as a method in which training load could be quantitatively evaluated (Foster *et al.*, 2017). The true value of scientifically monitoring training data to optimise training intensity and recovery was revealed when Sir Roger Bannister used interval training to break the four-minute mile (Foster *et al.*, 2017). The use of interval training meant that Rodger Bannister could assess improvements and deteriorations in his progress. His coach Frantz Stampfl, would give Roger Bannister time off to rest and recover when he was considered 'stale' (i.e., a term we now refer to as non-functionally overreached, see section 2.2.4) (Foster *et al.*, 2017). Through utilising this approach to training, Roger Bannister took active recovery and later broke the four-minute mile barrier, an accomplishment considered impossible by medical professionals at the time.

Technological advancements later allowed a more complex and thorough understanding of how exercise elicited physiological adaptations and consequently, stimulated improvements in performance. For instance, coaches and researchers alike could use objective internal measures such as heart rate monitors (Schneider *et al.*, 2018), blood lactate analysers (Swart and Jennings, 2004) and/or respiratory gas analysers. These measures could be used to track an athlete's response to a given training protocol and/or to test performance improvements (Balsom *et al.*, 1994a; Balsom *et al.*, 1994b). Arguably, one of the most innovative approaches, was later proposed by Foster *et al.* (2001). This method of monitoring workload is known as Session Rating of Perceived Exertion (sRPE). A player's sRPE score is calculated by multiplying their perceived exertion via Borg's CR-10 Ratings of Perceived Exertion (RPE) scale (Borg, 1998, see Table 2.1), by the duration of the exercise period. The sRPE score is then given in arbitrary units (AU). For example, a 40 minute training session with an RPE of 10 would result in a training session load of 400AU.

Table 2.1: Borg's modified CR-10 scale for measuring workload demands (Borg, 1998; Foster *et al.*, 2001).

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

In line with the aforementioned markers, RPE has been shown to accurately correlate with heart rate, blood lactate, and VO_2 data, amongst others (Chen *et al.*, 2002), making it one of the most practically useful, yet cost effective and simplistic approaches to monitoring training and match load (Comyns and Flanagan, 2013). Including sRPE data in the monitoring process means that steady state training, interval training, multi-mode training, resistance training and match play intensity can be accounted for (Foster *et al.*, 2001; Day *et al.*, 2004). Unsurprisingly, this approach has been used for the planning and implementation of periodisation strategies, tracking performance progress and investigating the load-injury relationship in elite contact team sports (Comyns and Flanagan, 2013; Rogalski *et al.*, 2013; Cross *et al.*, 2016; Williams *et al.*, 2017a; Stares *et al.*, 2018).

Noteworthy, however, are the limitations associated with the sRPE method when monitoring workload data in elite team sports. Firstly, sRPE is a subjective measure of internal load, meaning that high player adherence rates are needed to ensure accuracy and quality of the data when investigating workload data and injury risk. Consequently, if players do not enter their scores then the utility of the workload data to inform player status (i.e., fatigue) and injury risk is drastically degraded. Secondly, depending on when the RPE score is given, the last bout of exercise may influence the workload score (i.e., if the whole session was relatively light, but the final exercises drills were heavy, then the overall intensity rating may be overrated if taken immediately post exercise) (Foster *et al.*, 2001). Thirdly, if the scores between players are not confidential then athletes may provide lower or high scores to reflect those of their team mates (Minett *et al.*, 2021). The use of sRPE means that workloads are monitored through a combination of internal and external data, and one of the greatest limitations of this method is highly associated with the internal component. Utilising the external component of sRPE (i.e., training and match volume) only can remove these limitations since players are not required to provide the information. In addition, training volume (hours spent training) and match exposure (number of match involvements) have been shown to have significant associations with injury risk in Rugby Union (Brooks *et al.*, 2008; Williams *et al.*, 2017b; West *et al.*, 2019). The limiting factor of monitoring volume and exposure as a single risk factor, however, is that the exercise intensity for each individual is entirely neglected.

In the modern era of load monitoring, advancements in technology have allowed teams to use GPS devices housing IMUs to track on-pitch training and match loads in contact team sports like Rugby Union. For instance, distance covered, number of sprints performed, velocity of each exercising bout, acceleration and deceleration efforts and PlayerLoad™ scores can be monitored for every pitch-based training session and competitive match. This can be done for every individual, meaning the total demands of the team and position-specific demands can be tracked (Cunningham *et al.*, 2018; Howe *et al.*, 2017; Lindsay *et al.*, 2015; Pollard *et al.*, 2018; Reardon *et al.*, 2017b). In addition, individualised metrics for each player can be created (e.g., running distance covered at 60% of that players maximum velocity) so that coaches and practitioners can track the relative demands of exercise (Weaving *et al.*, 2018). Such data can be used to further understand the demands of that session/game for that specific player/positional group and can be used to help identify which players are fatigued or well-rested. This data has previously - and continually - shown ways in which coaches and practitioners can implement injury reduction strategies across multiple team sports (Bowen *et al.,* 2020; Colby *et al.,* 2014; Hulin *et al.,* 2016b; Malone *et al.,* 2018; Murray *et al.,* 2017b, 2017c).

As with all workload monitoring methods however, there are limitations with these devices. The accuracy and reliability of these devices is significantly reduced for short runs and changes of direction compared to running linearly for extended periods (Jennings *et al.,* 2010; Johnston *et al.,* 2012, 2014b). There are also concerns regarding the intraunit reliability and accuracy of these devices to quantify accelerations and decelerations and PlayerLoad^{TM} (Nicolella *et al.,* 2013; Barrett, 2016; Buchheit and Simpson, 2017). Furthermore, there are issues with IMUs being able to distinguish between tackles and changes of direction in team contact sports (Wundersitz *et al.*, 2015; Hulin *et al.*, 2017; Reardon *et al.*, 2017a), meaning that players may be reported to have been involved in more physically demanding situations than they were actually exposed to. One way this has been overcome in contact sports is the use of video coding (Reardon *et al.*, 2017a). Tracking players and coding contact events from video footage is a time consuming process, but it ensures accuracy when quantifying aspects of match play that are not possible through GPS and IMU devices alone. Together, these are some of the most utilised practices adopted in elite team sports today for monitoring external load and reducing injury risk.

2.2 PHYSICAL PREPARATION FOR PEAK PERFORMANCE & INJURY PREVENTION

2.2.1 Load and Recovery

Regardless of the professional sport in which an athlete competes, the goal of training is to continuously strive towards, and ultimately achieve a level of performance that is capable of winning at the highest level of competition (Gabbett, 2016a). Success in professional sport - particularly within a team sport environment - is repeatedly characterised by wins and losses (Wilson and Kerr, 1999). Consequently, to provide the best opportunity for success, athletes are put under intense physical training programmes that aim to stimulate exercise-induced adaptions and provide a platform for continuous progression. Training, however, is multifactorial, and key factors must be taken into consideration to ensure athletes of all stature are prepared for their position specific demands when competition arises (Lindsay *et al.*, 2015).

For an athlete to reach their performance potential, efficient preparation and effective planning are imperative (Lambert and Borresen, 2010). Athletes must be exposed to a sufficient degree of physical stress to induce fatigue, but also appropriate recovery periods to allow for adaptation to take place (Halson, 2014). The physiological stress an athlete is put under must therefore be administered, monitored and appropriately adapted for every athlete (Lambert and Borresen, 2010; Halson, 2014; Jones *et al.*, 2015). Failure to plan and implement a structured training programme may result in inappropriate levels of physical and/or emotional stress put on an athlete, resulting in a stagnant or even diminished physical capacity. In turn, this may cause a negative influence on performance (Busso, 2003; Meeusen *et al.*, 2013).

Of particular relevance to the human characteristic response to stress, is Hans Selye's 1956 publication, "*The Stress of Life*", which later assisted in the formulation of athletic improvement principles, specifically, the 3-stage theorem termed the general adaptation syndrome (GAS) (Seyle, 1956). The GAS model suggests that stress results in a disruption to the body's homeostatic state, and that a similar response is provoked irrespective of the physical (external) and/or psychological (internal) stressor involved (Seyle, 1956; Graeff, 2007). Selye pioneered the understanding of this adaptation process through presenting the theory of physiological alterations and corrections in homeostatic equilibrium following stress. The three stages are known as the 'Alarm Stage', the 'Resistance Stage', and the 'Exhaustion Stage' (Chiu and Barnes, 2003; Selye, 1956).

The Alarm Stage is initiated when stress is first recognized. Similar to that of the "fight or flight" response, this is associated with a rapid hormonal reaction, which serves to direct all energy to the external (or internal) threat (Graeff, 2007). When stress is recognised, the Hypothalamus-Pituitary-Adrenal (HPA) axis is stimulated, which involves the automatic surge of hormones like adrenaline, noradrenaline and cortisol into the bloodstream to provide instant energy (Graeff, 2007). This is a primitive response that results in an accelerated heart rate and respiratory rate. This response will remain for as long as the external threat exists, and once removed, the body will return to its normal state of homeostasis. If the stress continues or reoccurs for a period of time however, the body will make adjustments in its structures or enzyme level, forming a new homeostatic equilibrium to counteract the stressor. This is known as the Resistance Stage (Seyle, 1956), and rest must be allowed during this stage for recovery and improved physiological function to take place (Kellmann, 2010). The body's ability to continue this cycle is finite however, so if the stressor continues with no rest given, the body will eventually hit the Exhaustion Stage. This occurs through a depletion of energy reserves and negatively affects mental, emotional and physical abilities (Kellmann, 2010).

This theorem was later applied to the process of athletic training and recovery in the 1960s in an attempt to explain the process of athletic development following the application of training stressors. The GAS continues to provide a physiological rationale for appropriate recovery following training and competition stress, and is an essential aspect of an athletes training programme. It transpires to the training process, such that a training session triggers the Alarm stage, inducing a state of physiological fatigue. Consequently, the body is forced to regenerate in an attempt to return to a state of homeostasis, and it is during this return to homeostasis that physiological adaptations occur (Budgett, 1990; Meeusen *et al.*, 2013). This is provided adequate recovery is given however, in which the principle of supercompensation is attained (Meeusen *et al.*, 2013); where the adaptive responses to restore homeostasis improve beyond baseline, resulting in an increased state of performance potential (i.e., the athlete has adapted to the imposed training load and thus improved fitness) (Chiu and Barnes, 2003; Halson, 2014). This ensures that a similar training stimulus cannot disrupt the biological system to the same degree due to an improved work capacity. The next training stimulus must then be administered during this supercompensation phase to ensure progression is continually made. If however, during the supercompensation phase no training stimulus is given, then any training adaptations may diminish, resulting in pre-training homeostasis levels reoccurring. If the stress remains and sufficient recovery is not provided, then fatigue and eventually non-functional overreaching will occur. This may ultimately force recovery time to be taken otherwise illness and/or injury may become inevitable (Килttä and Hassmén, 1998) (See Figure 2.1).

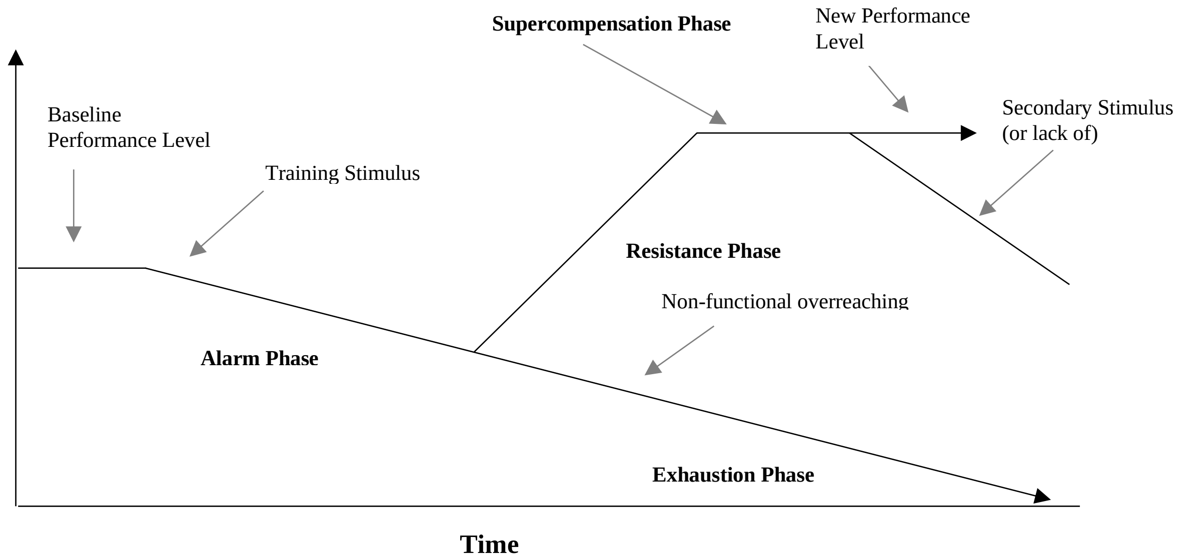


Figure 2.1: Seyle’s general adaptation syndrome (GAS) theory.

From a monitoring perspective, a clear understanding of the GAS is required to ensure effective training programmes are designed that optimise the relationship between training and improved performance. Inducing fatigue is necessary if an athlete is to enhance their current physical capacity to that of a higher level (Smith, 2003; Duthie, 2006). An appropriate training stimulus must adequately induce an acute fatigue response. It is overcoming this acute response that allows for tissue regeneration and improved performance (Budgett, 1990). Complications arise however, when the training programme adequately induces fatigue, but appropriate periods of recovery are not given - such as a secondary training stimulus being applied too early (Duthie, 2006). Without recovery, the negative training effects of fatigue may accumulate, resulting in reduced performance potential and increased injury risk, especially if the resultant is overtraining (Meeusen *et al.*, 2013). Conversely, if the training stimulus is insufficient to elicit an adaptive response, then athletes are exposed to under-loading, which will prevent the possibility of performance improvements being made (Kenttä and Hassmén, 1998).

Producing a training programme that considers and achieves an accurate balance between overloading and recovery is a complex task. The GAS can provide a skeleton on which a training programme can be built from, but the functioning of the training programme is complex and should not be oversimplified (Reilly *et al.*, 2009). Athlete monitoring systems must account for the level of fatigue induced, the training adaptations expected, the appropriate recovery time needed, when periods of overloading should be implemented, and times where underloading may be of benefit (Reilly *et al.*, 2009). Being able to adapt to any one of these variables to ensure athletes are continually progressing requires multifaceted and consistent monitoring. Stressors are additive, so ensuring the training stress implemented produces a recoverable level of fatigue within a practical amount of time takes careful consideration. This ties in directly with the Arndt-Schulz rule. Hugo Paul Friedich Schulz, a German pharmacologist and Rudolf Arndt, a German psychiatrist both discovered that small doses of toxins could have the opposite effect of large doses on yeast cells and animals. Such that, low doses of toxins could actually stimulate growth and fertility. It was found that:

"*For every substance, small doses stimulate, moderate doses inhibit, large doses kill*". Arndt-Schulz Rule, 1888.

The same principle applies to sports training and performance. An appropriate exercise stimulus in relation to an athlete's current physical capacity with sufficient recovery will allow for progressive overloading and improved performance over time. An overwhelming increase in training or match stress and stimuli without consideration to an athlete's current physiological capacity will drastically deteriorate the adaptive energy of the athlete, and rapidly increase exhaustion and injury risk. For an athlete to reach a state of homeostasis equilibrium following training requires the understanding of the physical load, as well as the athlete's perspective of the load applied (Susanne Kenttä and Hassmén, 1998; Lovell *et al.*, 2013). This will aid in the accurate implementation of load and recovery, allowing for supercompensation, and accordingly, enhanced performance.

2.2.2 Overtraining and Overreaching

Training for successful performance requires intensifying training beyond the current physical capacity of the athlete. This is termed overloading, and is an empirical aspect of the training process (Duthie, 2006). Overloading induces short-term performance decrements without provoking severe long-term negative psychological and/or physiological symptoms. It aims to result in functional overreaching, and coupled with adequate recovery, will lead to improved biological function and enhanced performance (Mujika *et al.*, 2018; Zatsiorsky & Kraemer, 1995), and a reduced risk of injury. **Functional overreaching** is where an athlete intentionally intensifies their training over a short period of time, resulting in heightened levels of fatigue. Sufficient rest is then scheduled so that a 'supercompensation*'* effect can occur, allowing the athlete to later exhibit an enhanced level of performance compared to previous baseline levels (Meeusen *et al.*, 2013; Zatsiorsky & Kraemer, 1995). When practitioners, coaches and/or athletes do not understand and respect this training process however, the relationship between training and recovery may cause non-functional overreaching (Meeusen *et al.*, 2013). **Non-functional overreaching** is caused when training is intensified over a long period of time without sufficient recovery periods, consequently hindering the 'rebound' effect of adaptation, and increasing the risk of injury.

In general, **overreaching** is defined as:

"*An accumulation of training and/or non-training stress resulting in **short-term** decrement in performance capacity with or without related physiological and psychological signs and symptoms of maladaptation in which restoration of performance capacity may take from **several days to several weeks***" (Meeusen *et al.*, 2013).

If non-functional overreaching persists, and the correct adjustments are not made, then eventually the athlete will evolve into a state of overtraining (Meeusen *et al.*, 2013) (See Figure 2.2). **Overtraining** is defined as:

"*An accumulation of training and/or non-training stress resulting in* ***long-term*** *decrement in performance capacity with or without related physiological and psychological signs and symptoms of maladaptation in which restoration of performance capacity may take* ***several weeks or months***" (Meeusen *et al.*, 2013).

Although beyond the scope of this thesis, it is crucial to understand that continuous, relentless 'intensified training' with poor or even no recovery period, can lead to a stagnation or reduction in performance output that can last for several weeks, months, or even years (Meeusen *et al.*, 2013). While this may be unlikely to occur at the professional level, it does promote the importance of understanding an athlete's response to training and match workload for performance optimisation, injury risk reduction, and ultimately player welfare maintenance.

PROCESS	TRAINING (overload)	INTENSIFIED → TRAINING		
OUTCOME	ACUTE FATIGUE	FUNCTIONAL OR (short-term OR)	NON-FUNCTIONAL OVERREACHING (extreme OR)	OVERTRAINING SYNDROME (OTS)
RECOVERY	Day(s)	Days – weeks	Weeks – months	Months - …
PERFORMANCE	INCREASE	Temporary performance decrement (e.g., training camp)	STAGNATION DECREASE	DECREASE

Figure 2.2: Various stages of training, overreaching and overtraining.

Taken from: Meeusen, R., Duclos, M., Foster, C., Fry, A., Gleeson, M., Nieman, D., Raglin, J., Rietjens, G., Steinacker, J. and Urhausen, A. (2013) 'Prevention, diagnosis, and treatment of the overtraining syndrome: Joint consensus statement of the european college of sport science and the American College of Sports Medicine', *Medicine and Science in Sports and Exercise*, 45(1), pp. 186–205.

2.2.3 Understanding the Athlete Response to Training and Competition Workloads

An athlete's training response following a given workload is extremely individualised (Viru and Viru, 2000; Meeusen *et al.*, 2013), and will elicit varying degrees of fatigue and fitness improvements, depending on the athlete's current workload capacity. Therefore, monitoring player load is of particular importance if coaches and practitioners are able to accurately assess where any athlete sits along the fitness/fatigue spectrum. Planning and implementing a training programme that adequately stimulates exercise-induced adaptations, whilst also allowing for sufficient recovery is a challenge for coaches working in elite sport. Fluctuations in an athlete's training response (e.g., across and between days, and within micro-cycles), make it particularly difficult to provide an individualised workload and recovery plan for every athlete (Gamble, 2006). This is because there is a variety of factors that can and will continually interact with the outcomes of fitness and fatigue, such as physical capacity, exercise tolerance, recovery potential and life stressors (Morgan, 1973; Klenttä and Hassmén, 1998). The planning, preparation and implementation of a flexible and adaptive training programme that considers modifiable risk factors (e.g., external workloads) is thus key for ensuring every athlete is given an optimal work-to-rest ratio that elicits exercise-induced adaptations, and thereafter, allows the deleterious effects of fatigue to diminish (Lambert and Borresen, 2010).

This is particularly difficult within Rugby Union where the competitive phase of a season consists of regular matches (i.e., Rugby Union's PRO 14 competition), coupled with both a combination of players being selected for International play (i.e., Rugby Union's Autumn Tests or Six Nations competitions), as well as professional clubs progressing through the various stages of additional competitions (i.e., Rugby Union's Challenge and Champions Cup competitions). Players must therefore be prepared for a variety of challenges across various levels of play. This may be amplified when players are selected for their international team because the training loads prescribed will likely reflect a higher volume, intensity and frequency of training, depending on the strategies and playing styles adopted for that level of competition.

Due to the variety of player roles in team sport environments like Rugby Union, players must be exposed to an exercise stimulus that allows them to develop the skills and attributes necessary to dominate at their particular position (Reilly *et al.*, 2009). The challenge with this is that players will elicit various training responses depending on the stress they are put under. Depending on the motor units and muscle fibres recruited, the load put on the athlete and/or the force production and velocity used to complete the task (to name a few), different adaptation responses at the tissue level will be seen (Reilly *et al.*, 2009). For example, scrummaging (i.e., an isometric exercise involving an extremely high force production over a long period of time) will elicit a very different physiological response compared to agility work (i.e., short intervals of fast paced dynamic work involving rapid changes of direction). The training type and activity will also influence the level of mitochondrial biogenesis, the expression of growth factors, cellular apoptosis, amongst other key molecular responses (Reilly *et al.*, 2009). Indeed, in the words of Charles Darwin:

"*It is not the strongest of species that survives, not the most intelligent that survives. It is the one that is the most adaptable to change*".

For example, in Rugby Union, if the Back positions focus on developing speed and power through plyometric training then this will elicit a training response that stimulates the structural adaptation needed to make the cell stronger for the next plyometric training session (i.e., a rapid dynamic switch from eccentric to concentric contraction, the force produced per unit time and the ability of the motor unit to recruit muscle fibres rapidly) (Reilly *et al.*, 2009). However, if Forward positions work on scrummaging, then these players are required to perform maximal isometric contractions over extended periods of time. This isometric strength and power work will elicit an entirely different training response to plyometric work. Indeed, exercise improvements in isometric strength training are greatest at the joint angles exercised (Reilly *et al.*, 2009); and are unlikely to extend to dynamic work where joint angles are constantly changing. Therefore, it is important to understand that there will always be variation between players completing both gym-based and pitch-based work or competing within the same match, which is all dependent on their positional role, and the physical attributes needed to excel in that role.

In Rugby Union, the tackle and collision loads placed on athletes adds a unique and challenging prospect for coaches to consider when trying to elicit a given exercise response to training and/or developing robustness for match play. To remain injury free, all players must be able to withstand, as well as effectively perform and dominate the high-impact collisions associated with Rugby Union. Accordingly, being able to account for, and monitor the loading associated with these contact events, as well as the training administered to improve physiological performance is important (Clarke *et al.*, 2013). Players may be exposed to different training stressors in an effort to optimise various levels of performance, however the accumulation of these different physical stressors will induce fatigue within players (Williams *et al.*, 2017a). In turn, this increase in physical fatigue will result in a reduction in the stress-bearing capacity of musculoskeletal soft-tissue (Kumar, 2001; Williams *et al*., 2017a). During match play, musculoskeletal soft-tissue must attenuate excessive forces created during high impact events. Therefore, if the stress-bearing capacity of musculoskeletal tissue is compromised in training and sufficient recovery is not given prior to match play, the likelihood of injury is considerably increased. It is imperative that strength and conditioning coaches consider an athlete's response to external training loads, and how these can both increase and reduce the risk of injury. The challenge is that coaches must also consider that if players are not placed under appropriately high physical loads, then they may not be conditioned enough to tolerate the high impact loads associated with Rugby Union match play, in turn this will also result in a heightened injury risk due to a lack of exercise tolerance. An important method used by team coaches and practitioners to ensure athletes are well conditioned for the demands of the sport is to monitor player workloads. This allows coaches to assess a player's current workload capacity, whereby strategies can then be put in place to ensure improvements are being made. An adequate monitoring programme that balances an appropriate external load with sufficient rest and recovery will help in ensuring exercise tolerance, robustness and overall resilience are optimised for Rugby Union players.

2.2.4 Summary

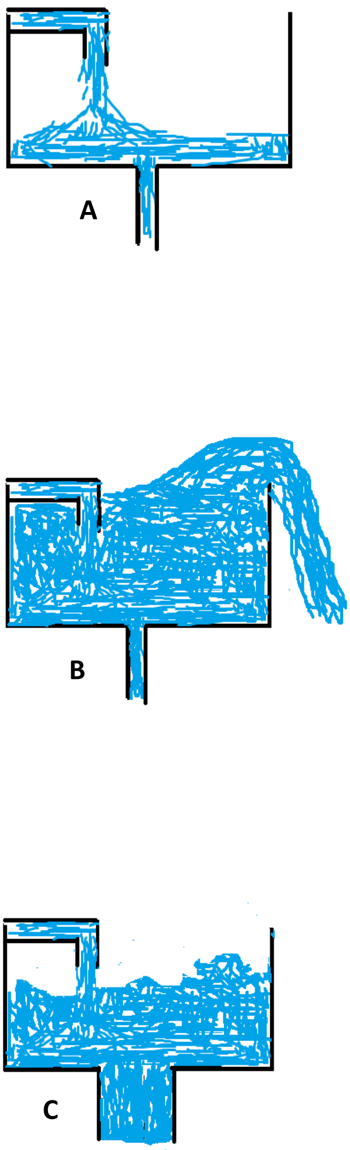


Figure 2.3: (A) Low stress but sufficient recovery; (B) High stress and insufficient physical capacity to recover; (C) High stress but improved physical capacity to sufficiently recover.

Observe the 'work capacity sink analogy' (Figure 2.3). The training and competition stress an athlete is exposed to is characterised by the water flowing out the tap. The plughole represents that athlete's current physical capacity to tolerate and recover from that given workload. As depicted in Figure 2.3A, when training (or match) load is low there is a small trickle of water flowing from the top (stress), and the plughole does not have to be very large in order to drain it (physical capacity and recovery). Given the demands of Rugby Union match play, a coach may elicit smaller workloads as not to put an athlete into a state of non-functional overreaching. However, this also has the negative consequences of a lack of conditioning that prevents players adapting to appropriate loads and building up the resilience needed to remain injury free, particularly during match play.

On the other hand, in an effort to maximise physical adaptation and performance, players may be exposed to a workload stress and stimuli that exceeds a player's current physical capacity and recovery potential (Figure 2.3B). In turn, chronic fatigue via non-functional overreaching may ensue, resulting in a reduction in the stress bearing capacity of the musculoskeletal soft-tissue, and a higher injury risk.

With a well-structured and adaptable training programme that gradually and systematically caters for a greater flow of water (i.e., external workload), through consideration of the athlete's current workload capacity and recovery potential, then appropriate adaptation will be achieved. In turn, this will result in performance improvements, and importantly, greater resilience and robustness to greater stressors that could cause injury, particularly during Rugby Union match play (Figure 2.3C).

2.3 THEORIES AND MODELS FOR PERFORMANCE AND INJURY PREVENTION

2.3.1 An Athletic Systems Model for Performance – The Impulse-Response Model

Early work by Bannister *et al.* (1975) and Calvert *et al.* (1976), attempted to offer a quantitative conceptualization of how athletic performance was influenced by the process of physical training via a systems impulse-response (IR) model. Bannister *et al.* (1975), proposed a systems model which suggested that the input component (training stress) of performance was multidimensional and was made up of four fundamental determinants: (1) cardiovascular, (2) strength, (3) skill and (4) psychological factors (See Figure 2.4). Authors highlighted that the weighting of each model determinant on performance would vary from sport to sport (e.g., a cyclist needs endurance, but weak legs muscle would greatly hinder performance), but that the structure explains the fundamentals of training and performance output (Calvert *et al.*, 1976).

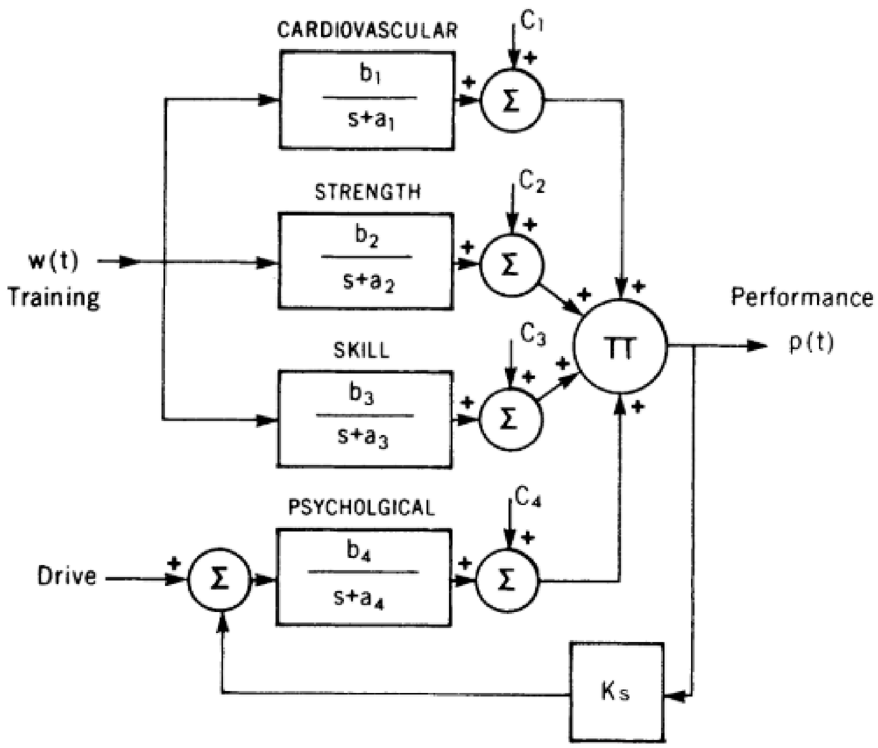


Figure 2.4: The athletic systems model (Bannister et al., 1975; Calvert et al., 1976).

However, while attempting to combine the various components of this four-component model, authors encountered problems. Consequently, Calvert *et al.* (1976), used a simplified model to quantifying the training-performance relationship. The model was based on the positive and negative functions associated with future performance output following training. Three simplified components were used that made up the following mathematical equation:

Model Performance = (fitness from training model) – K (fatigue from training model)

(Eq. 1)

Where K is the constant that adjusts for the difference between the fatigue and fitness responses to training.

Calvert's model has various forms, but the final was made up of two components for fitness and one component for fatigue:

$$p(t) = [(e^{\frac{-t}{\tau_1}} - e^{\frac{-t}{\tau_2}}) - Ke^{\tau_3}] * w(t)$$

(Eq. 2)

Where $w(t)$ is the training impulse, and $p(t)$ is the rise in performance, with a time constant in days (τ). The fitness functions were associated with the time constants τ_1 and τ_2, and the time constant τ_3, was associated with fatigue. The day of the training impulse was symbolised by t and * indicates the convolution. τ_1 and τ_2 are the time constants associated with the two fitness functions and τ_3 is the time constant associated with fatigue. Individualised determination for time constants and the fatigue coefficient (K) were carried out for each athlete.

Authors noted that performance capacity decreased when training load was increased, and that the decaying rate of fitness and fatigue largely varied (Calvert *et al.*, 1976). The IR model was particularly beneficial because the training data (input data) was collected from the individual, and therefore performance predictions were specific to that individual (Taha and Thomas, 2003). The IR model was thus an individualised training tool that quantitatively links ability (performance) at a given time point, to the cumulative influence of prior training loads (Clarke and Skiba, 2013). In their study, fitness decay was estimated to be 50 days, whereas the decay rate of fatigue was just 15 days. Authors highlighted that the interplay between the fitness and fatigue impulse was the most interesting feature in the model, and that the dominant impact of fatigue on performance was 'surprising' (Calvert *et al.*, 1976). Importantly, Calvert *et al.* (1976), did highlight that feedback and feedforward loops were present in the model which increased the models complexity. For instance, skill and strength may feedback to psychological factors, whereas psychological factors (e.g., motivation, concentration and biofeedback information) may fast forward to skill and strength (Calvert *et al.*, 1976).

Therefore, performance is both progressed and hindered through multiple input channels. Nevertheless, Calvert *et al.* (1976), highlighted that this model was a mere skeleton of the what a comprehensive model of training and performance would end up being, and likely lacked the true complexity of training and the detriments of fitness and fatigue.

2.3.2 Subsequent Fitness-Fatigue Models

Based on Hans Selye's GAS theorem and later work by Bannister and colleagues, (1975), subsequent research expanded on the impulse-response model, which previously highlighted that an exercise stimulus induces two response functions: (1) fitness (positive function) and (2) fatigue (negative function). Given the challenges associated with quantifying the intangible performance factor of psychological status, Morton *et al.* (1990), further simplified the model to a 2-component system based on the training dose effect of fitness and fatigue on athletic performance (See figure 2.5).

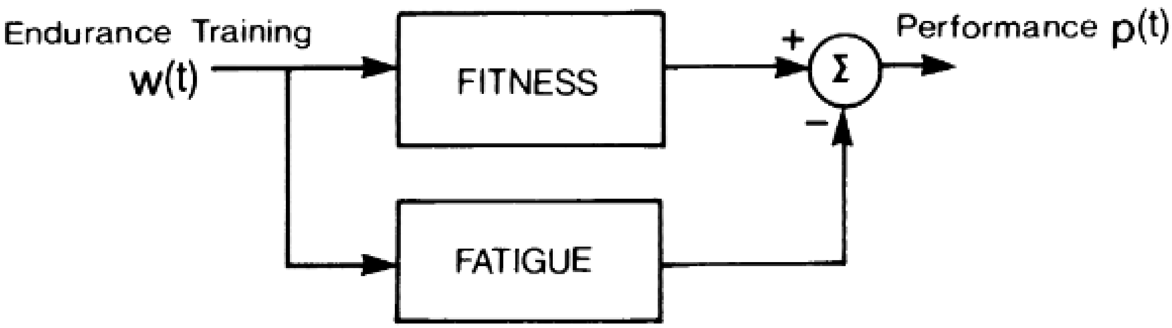


Figure 2.5: Simplified 2-component training vs. performance model from Morton *et al*. (1990). Training input dose W(t) influences both fitness and fatigue, these functions are combined by ∑ (fitness positively and fatigue negatively) into a single performance output p(t).

The 2-component equation was given by:

$$\mathrm{g}(t) = \mathrm{g}(t-i)e^{\frac{-i}{\tau_1}} + w(t)$$

(Eq. 1)

&

$$\mathrm{h}(t) = \mathrm{h}(t-i)e^{\frac{-i}{\tau_2}} + w(t)$$

(Eq. 2)

Where each time a player has a training input [w(t)], fitness [g(t)] and fatigue [h(t)] both have different response levels at the end of each day (t), The intervening period between the current days training compared to the previous days training (i), is also considered. As well as the decay time constants of these respective effects (τ_1 and τ_2). Weighting factors were then given to fitness and fatigue (k_1 andk_2, respectively), by combining the aforementioned equations to produce a simple linear difference equation. Morton *et al.* (1990), provide an example of this on theoretical data in their paper:

$$p(t) = k_1 \mathrm{g}(t) - k_2 h(t)$$

(Eq. 3)

When using this model, authors selected duration of training and heart rate responses to training. This was based on the accuracy and ease of data collection for these variables and their ability to be modified, rather than observed (Morton *et al.,* 1990) - as would be the case with psychological factors. The difference between the positive training effects of fitness, and the negative training effects of fatigue provided the performance outcome, which - as with previous work conducted by Bannister *et al.* (1975) and Calvert *et al.* (1976) - was suggested to change over time. Following exposure to training stress, physical capacity is decreased due to the negative training effect of fatigue outweighing the positive training effect of fitness. However, as previously shown, the negative training response of fatigue dissipates at a much faster rate than fitness, such that fitness eventually outweighs fatigue (Clarke and Skiba, 2013). Over time, if the negative training effect of fatigue is allowed to subside between exercise bouts, the cumulative fitness effects of long-term training will lead to greatly improved physical capacity (Bompa, 1999). These mathematical models therefore manage to capture much of the important physiology associated with training and competition stress and stimuli, and the resulting adaptations of the body (Taha and Thomas, 2003). For instance, overreaching is apparent following the appropriate training dose, resulting in a stagnation or decrease in performance capacity. The model can also capture (1) the probable plateau effect associated with insufficient rest; (2) the positive supercompensation effect following tapering/recovery following overloading, and (3) the decay of training induced adaptations when training is ceased or markedly minimised (Clarke and Skiba, 2013), all of which are reversible and individualised.

Numerous studies thereafter attempted to use similar structures to provide convincing scientific evidence of the link between the training process and performance outcome via quantitative models (Busso *et al*., 1991; Fitz-Clarke *et al*., 1991; Busso *et al*., 1994; Taha and Thomas, 2003). For instance, Busso *et al*. (1991) applied their own systems structure equation to model the effects of training on performance, whereas Fitz-Clarke *et al*. (1991), later fitted an influence curve in their model to clearly indicate how a training session could affect performance at a specific point (i.e., for any given day). Furthermore, Busso *et al*. (1994), later used the functions of fitness and fatigue to model athletic performance in a hammer thrower. Authors considered the variations in performance via the negative (NF) and positive (PF) functions associated with fatigue and fitness estimated in previous studies (Busso *et al*., 1994). Authors then used an adapted method from a combination of NF and PF, where the negative influence of fatigue (NI) and positive influence of fitness (PI) were mathematically related to performance based on training exposure. Beyond just mathematical modelling, Chiu and Barnes, (2003), proposed that there are fitness and fatigue effects on more than one system of the body, and that a specific training stimuli will elicit a different (e.g., metabolic musculoskeletal, immunological) response. Authors highlighted that the summation of the after-effects of fitness and fatigue on all of these systems is what ultimately represents preparedness (i.e., physical capacity).

An important point of consideration however, is that all of these models are more accustomed to athletes competing in individual competitor sports, which is why they have been applied to swimming (Bannister *et al.*, 1975; Calvert *et al.*, 1976), running (Morton *et al.*, 1990), cycling (Busso *et al*., 1991), and hammer throwing (Busso *et al*., 1994), amongst others. In addition, studies are often confined to laboratory settings which limit their external validity. It has been reported that such methods would likely result in poor adherence rates in team sport environments due to athletes having to enter their own input data (Clarke and Skiba, 2013). Models that use HR data are also limited by the multiple intrinsic and extrinsic factors that influence HR data outputs. For instance, physiological (e.g., neurological, endocrine, respiratory), psychological (e.g., emotions, stress, motivation), lifestyle (alcohol and tobacco levels) non-modifiable factors (e.g., age, sex, ethnicity) and variations in the training process (e.g., volume, aerobic steady state training vs. HIIT) will all influence HR data (Buchheit, 2014; Fatisson *et al.*, 2016; Schneider *et al.*, 2018). A fundamental limitation of this data is that it is heavily influenced by hydration, illness or cardiac drift, and fails to accurately record the workload intensity of high intensity interval type work, that often exceeds workloads at $VO_{2\ max}$ (Laursen, 2010; Clarke and Skiba, 2013). Another limitation of these previously proposed models is that they fail to consider the multifactorial nature of athletic injury. Indeed, injury is highly associated with fatigue and fitness principles, but there are multiple risk factors that often come together to result in injury occurrence (Meeuwisse, 1994). Consequently a number of multifactorial modelling approaches have been proposed.

2.3.3 Multifactorial Model of Sports Injury Causation

It is well documented that injury risk in sport is multifactorial (Meeuwisse, 1994; Meeuwisse *et al.*, 2007; Soligard *et al.*, 2016; Windt and Gabbett, 2016), and that multiple limitations are associated with studies assessing single risk factors via univariate methodological approaches (Meeuwisse, 1994). These studies fail to accurately measure the true nature of injury risk and ultimately hinder the ability of coaches and practitioners to identify 'at risk' players. Meeuwisse, (1994), later provided a multifactorial modelling approach to further understand athletic injury causation (see Figure 2.6).

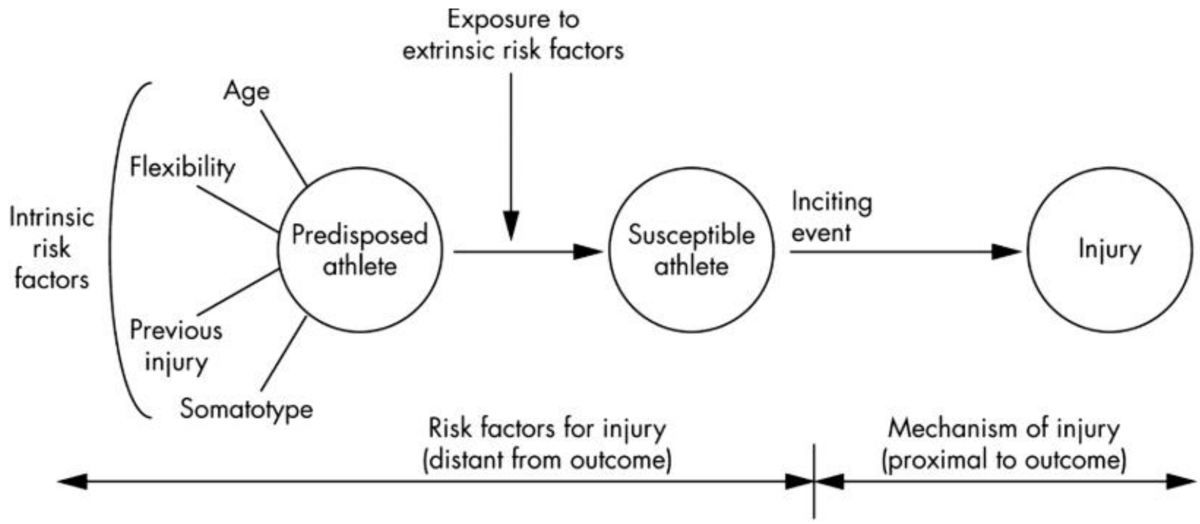


Figure 2.6: The multifactorial model developed by Meeuwisse, (1994).

Within a multifactorial model, there are both modifiable and non-modifiable injury risk factors. For instance, a player's age and inherent genetic pre-disposition or previous injury history are non-modifiable intrinsic risk factors, whereas flexibility and body mass are modifiable intrinsic risk factors. Extrinsic risk factors, such as playing surface, opponent behaviour or sports protection can also influence the susceptibility of injury (Windt and Gabbett, 2016). These intrinsic and extrinsic risk factors are interrelated and will either increase or reduce a player's likelihood of injury during training or competition. For example, a Rugby Union player colliding with an aggressive opponent may be more susceptible to a shoulder injury if they carry a history of rotator cuff issues. More recent research has also built upon the initial multifactorial model proposed by Meeuwisse, (1994). Meeuwisse *et al.* (2007), developed a new model in the form of a 'dynamic, recursive injury aetiology model' (see Figure 2.7). One of the most important acknowledgments in this paper was that injury risk is dynamic and not necessarily linear. Fundamental to the training process is the understanding that training or competition loads that do not result in sustained injury can actually modify injury risk via exercise-induced adaption (Meeuwisse *et al.*, 2007; Windt and Gabbett, 2016). Consequently, this model provided an important frame-work for coaches and practitioners to use when considering load-injury relationships.

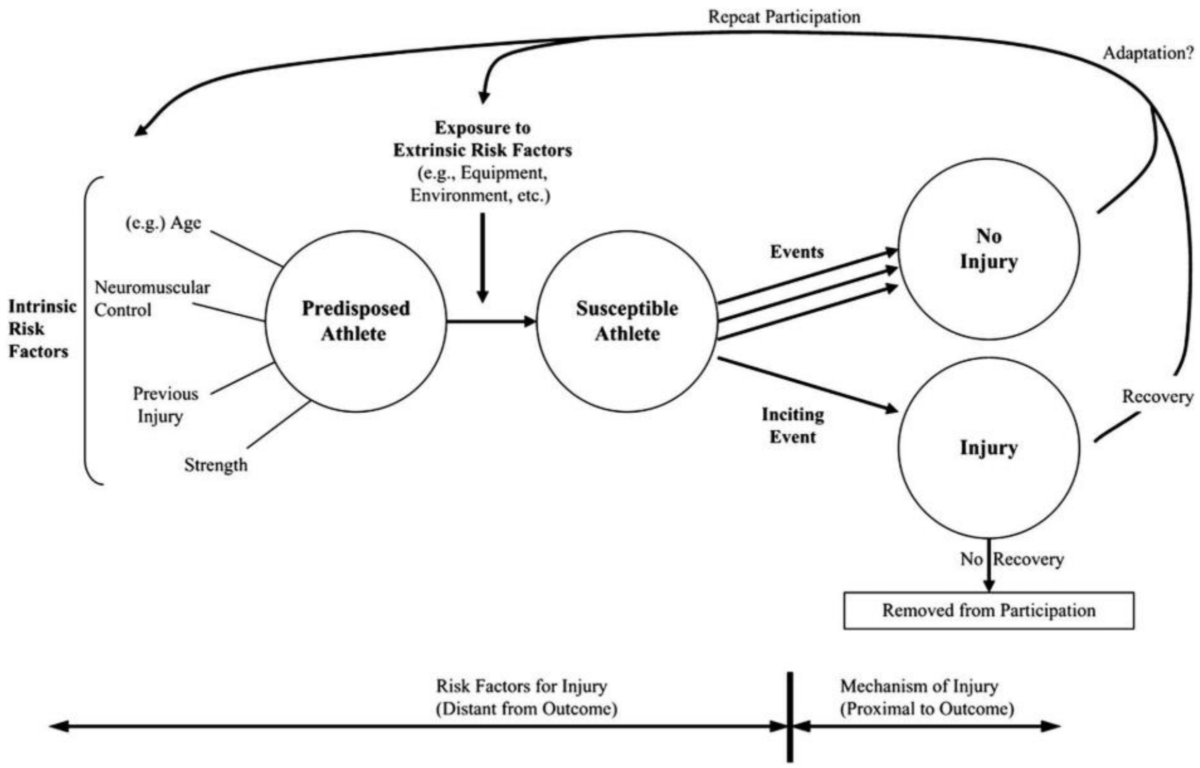


Figure 2.7: The dynamic, recursive model developed by Meeuwisse et al. (2007).

2.3.4 The Conceptual Framework of Physical Training

Beyond the sophisticated quantitative analysis methods adopted by previous research (Bannister *et al.*, 1975; Calvert *et al.*, 1976; Morton *et al.*, 1990; Meeuwisse, 1994) to mathematically quantify fitness and fatigue responses to training and corresponding performance outcome, Impellizzeri *et al.* (2005), developed a qualitative load monitoring model to understand and control the training prescribed for team sport athletes. Originally this model considered both the implications of fitness and fatigue - as with previous research (Bannister *et al.*, 1975; Calvert *et al.*, 1976; Morton *et al.*, 1990) - but also showcased the interaction and importance of internal loading responses to external (modifiable) load. More recently, a revised model has been published by Jeffries *et al*. (2021) (see Figure 2.8).

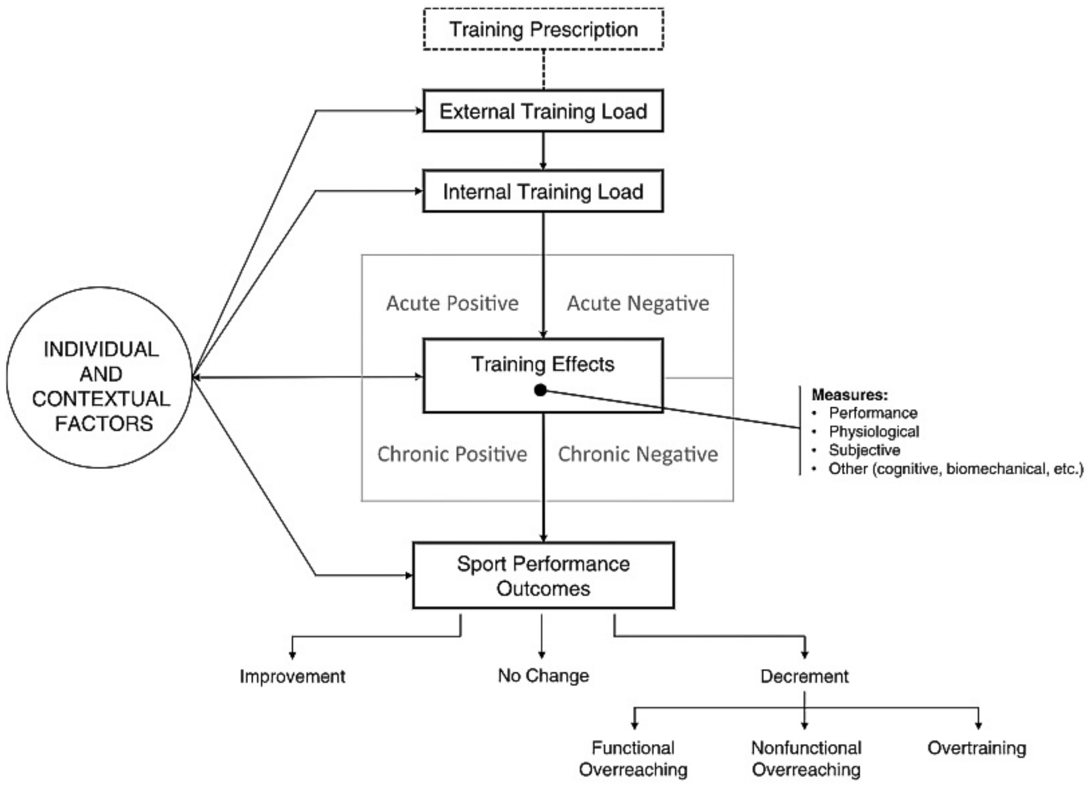


Figure 2.8: Conceptual framework of physical training. Model Taken from Jeffries *et al.* (2021).

Previously, Impellizzeri *et al.* (2005), conducted a study with a group of 15 junior soccer players to provide evidence that even when external training load is similar between players, there can still be large individual internal loading differences (quantified via heart rate at the lactate threshold and onset of blood-lactate accumulation [OBLA] following different times spent in different exercise intensity zones) between players, due to individual player characteristics. The findings reported by Impellizzeri *et al.* (2005), highlighted that athletes exposed to the same loading conditions will not elicit the same internal response, meaning that even when the external load of training is standardised, the internal load may vary due to diverse individual characteristics.

The qualitative load monitoring model previously provided by Impellizzeri *et al.* (2005), was useful in our understanding of how individual factors may directly influence a player's internal response (and ultimately their training outcome) when exposed to the same external load. A limitation of this theoretical model however, was its lack of other training elements. Indeed, Jeffries *et al*. (2021), identified that one of the most relevant models previously proposed for the training process was the Banister Impulse-Response model due to its measurable components and concepts (as aforementioned, these are the positive and negative elements of fitness and fatigue). These constructs were not included in the original model proposed 15 years ago. Therefore, Jeffries *et al*. (2021), included these aspects, but refrained from using the terms 'fitness' and 'fatigue', given that these terms have a multitude of meanings and may result in confusing overlapping due to a number of generic definitions, depending on the context in which they are used. Therefore, the contextual framework of physical training simply refers to the positive and negative effects of training. As with the integration of other frameworks (e.g., the Banister Impulse-response model), Jeffries *et al*. (2021), also integrated the joint consensus statement of the European College of Sport Science (ECSS) and the American College of Sports Medicine (ACSM) on overtraining (Meeusen *et al*., 2013). This allowed the conceptual framework to consider the short (acute) and long-term (chronic) effects of physical training based on the balance of positive and negative outcomes on sports performance. All of which are influenced by individual (e.g., genetics, training status, nutrition, current health) and contextual (e.g., environmental, cultural, social) factors (Jeffries *et al*., 2021).

It is important to understand how the negative and positive acute and chronic constructs of the conceptual model relate to the training process. An athlete's ability to cope with the demands of the external workload will directly impact how the negative effect of training impacts the acute performance outcome (i.e., functional overreaching following intensified training that is planned may result in diminished performance over an acute timeframe, but thereafter result in a positive sports performance outcome following recovery). An unplanned deterioration in performance may indicate that the training prescription is not suitable for the athlete, whether this be due to individual or the contextual factors (Jeffries *et al*., 2021). Therefore, modulation of the external workload is necessary to prevent the negative training effects becoming a chronic problem. This can be overcome by using feedback from the training effects (Jeffries *et al*., 2021). For instance, following external load, the negative effects of training may result in diminished performance (i.e., via performance testing) and/or increased subjective levels of muscle soreness. These are common and may be influenced by the exercise prescription. It is only when these negative effects do not follow the laws of progressive overloading and begin to show signs of, for example, over training, that modulation of the model (i.e., adaption to the prescription) becomes necessary.

2.3.5 How much is too much? The workload—injury aetiology model

Understanding the body's physiological response to external load (i.e., frequency, intensity, duration or mode of exercise) is of vital importance (Soligard *et al.*, 2016). Based on the characteristics of how the external stress and stimuli is applied to an athlete, different internal responses to the cardiovascular, neuromuscular, musculoskeletal and/or metabolic systems will occur (Soligard *et al.*, 2016; Windt and Gabbett, 2016). It is well understood that exposure to external load will decrease physical capacity and induce fatigue, but that following appropriate recovery, positive adaptations will be elicited that improve workload capacity and increase athletic resilience to external force, consequently increasing performance output and subsequently providing protection against injury risk (Windt and Gabbett, 2016). If this ensues at an appropriate level (i.e., follows the laws of progressive overload and sufficient recovery), athletes will continue to gain marginal increases in performance and physical robustness (see Figure 2.9) - assuming outlying factors are well-balanced (nutritional state, sleep quality, readiness and motivation to train etc.).

Indeed, injury aetiology models have highlighted the interplay between both intrinsic and extrinsic factors in sport, and the emerging importance of controlling for both (if modifiable) (Soligard *et al.*, 2016). However, beyond just measuring the physiological and psychological internal responses to external load, actually quantifying what the external load consists of, and the associated risks of poorly balancing load and recovery is fundamental in the training-performance continuum (Drew and Finch, 2016). Athletes and coaches are continuously and relentlessly pushing the boundaries of their volume and intensity in an effort to optimise performance, which unsurprisingly, is mainly achieved through the adaptation to the structure and function of their training programme (Soligard *et al.*, 2016). If the training process and periodisation strategy adopted by team coaches does not adequately account for the deteriorating effects of excessive external loading or the need for tapering and recovery, then the micro damage within the tissue structure may deteriorate tissue loadbearing capacity, resulting in an increased risk of injury (see Figure 2.10).

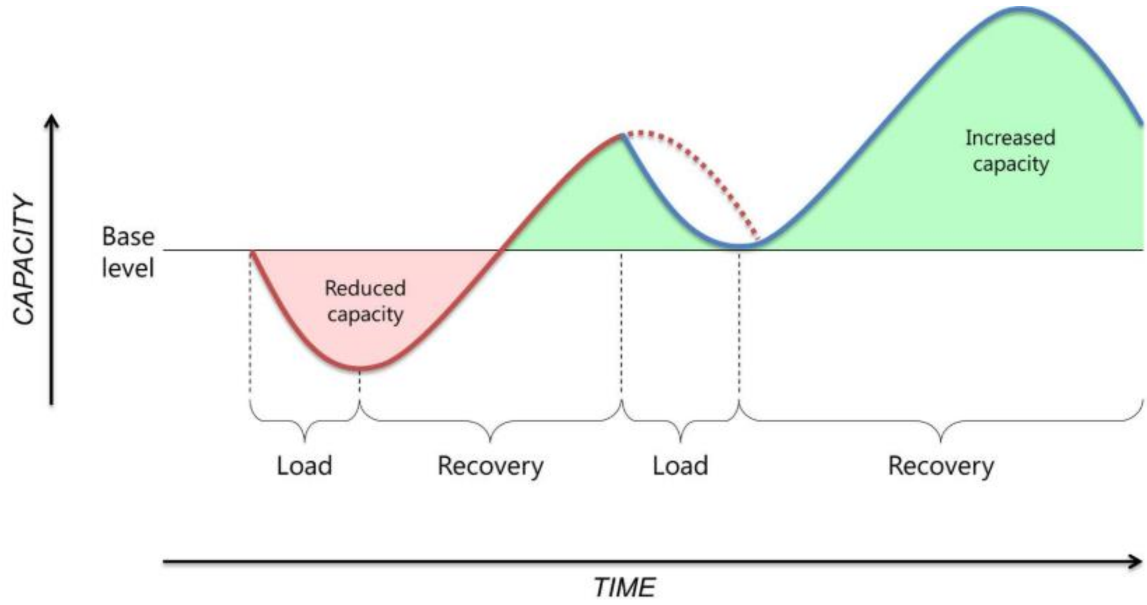


Figure 2.9: Cycles of load and recovery impact physiological adaptation. Taken from Soligard *et al*. (2016).

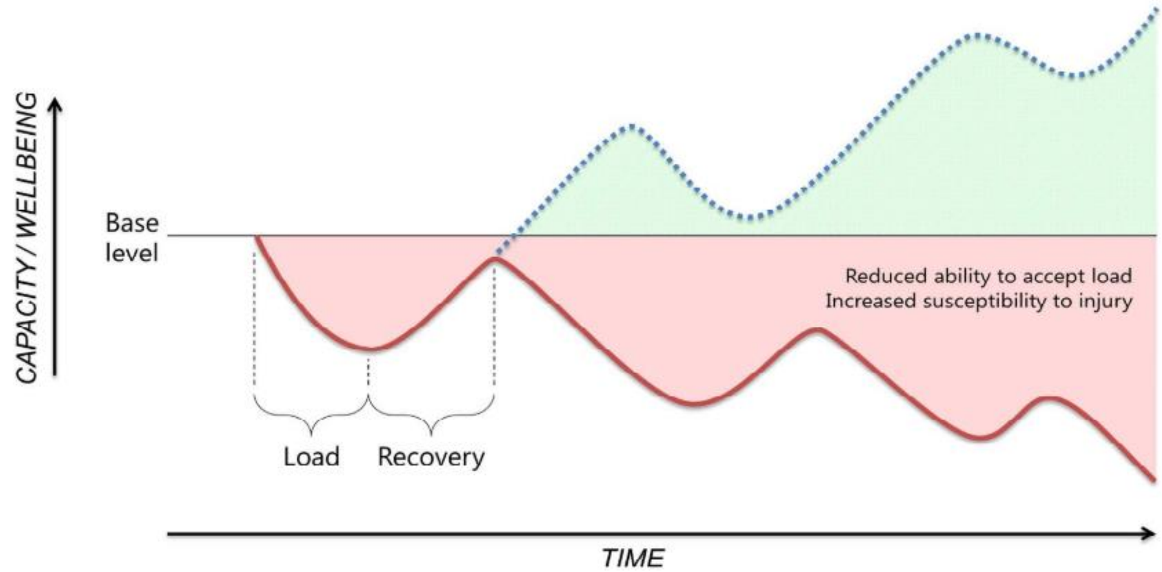


Figure 2.10: Cycles of excessive load or inadequate recovery will result in maladaptation. Taken from Soligard et al. (2016).

Based on the ideology of Soligard *et al.* (2016), and that of previous models (Bannister *et al.*, 1975; Calvert *et al.*, 1976; Morton *et al.*, 1990; Meeuwisse, 1994; Impellizzeri *et al.*, 2005; Meeuwisse *et al.*, 2007), Windt and Gabbett (2016), created the workload—injury aetiology model (see Figure 2.11). Authors provided a more comprehensive evaluation of how both modifiable and non-modifiable intrinsic risk factors are associated with workload (i.e., possibility to adapt following workload), and the dynamic nature of injury and performance following training or competition loads, similar to the dynamic recursive model of Meeuwisse *et al.* (2007) but the primary process for performance and injury outlined by Windt and Gabbet

(2016), was the 'Application of Workload' (i.e., the influence of external load). Authors presented the athlete as a 'vehicle' moving through the training process. Similar to that of Bannister's early model on performance outcomes (Bannister *et al.*, 1975; Calvert *et al.*, 1976), and Soligard and colleagues (2016) model for injury susceptibility, Windt and Gabbett, (2016), combined both to highlight that an the athlete may be driven towards positive or negative consequences following exposure to external load. In addition, in line with Meeuwisse *et al.* (2007), Windt and Gabbett, (2016), highlighted that repeated exposure to external stimuli can alter the subsequent injury risk, which occurs due to positive exercise-induced adaptations or negative maladaptation from training and competition loads. A fundamental gap in previous models was the exclusion of rehabilitation and return-to-play (RTP) processes. This is considered in the workload—injury aetiology model, as injured athletes rely on an appropriate training structure and an adequate training stimuli to the injured tissue to restore resilience Windt and Gabbett, (2016). Therefore, in order to optimise performance, minimise injury risk and enhance the return-to-play process, repeated and consistent monitoring of modifiable external risk factors is imperative (Windt and Gabbett, 2016).

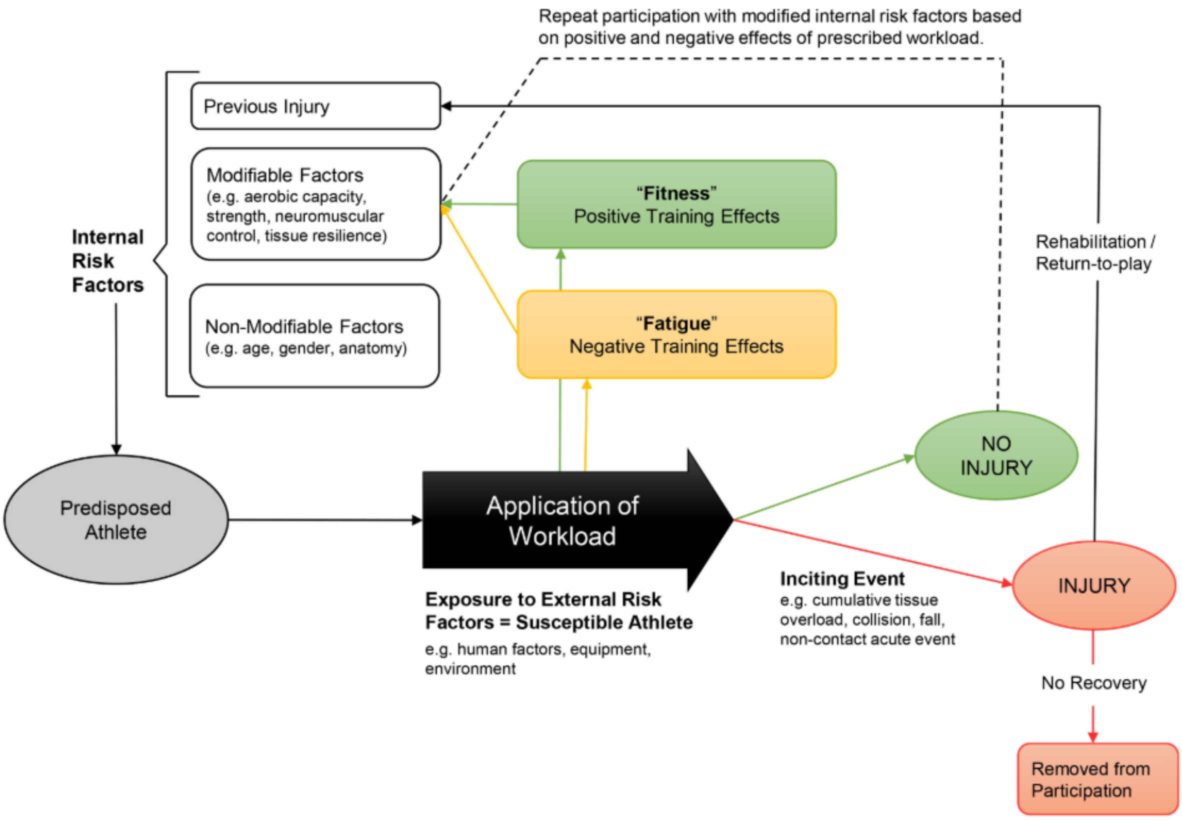


Figure 2.11: The workload-injury aetiology model (taken from Windt and Gabbett, 2016).

2.3.6 Summary

The evolution of athletic performance modelling has provided sport scientists, coaches and researchers with a complex scientific approach for monitoring training and match loads in the modern era. Although the internal response of an athlete's exposure to external load is imperative to wellbeing, success and importantly, injury risk, recent research has begun to focus largely on the external workload completed by athletes, and the injury risk associated with this in elite team sport (Soligard *et al.*, 2016; Windt and Gabbett, 2016). This is largely due to the fact that, without external workload, there is no relationship to investigate. Owing to emphasis of this, the following sections focuses on the methodological approaches of collecting and analysing injury data, and how contemporary measures of external workload in team sport have used these load measures in conjunction with injury data to investigate player injury risk.

2.4 METHODOLOGICAL APPROACHES TO MEASURING INJURY RISK

2.4.1 The Consequence of Injury in Rugby Union

Long after professional Rugby Union players retire, the injuries sustained during their sporting careers can have long-term consequences on their quality of life. For instance, Davies *et al.* (2017), conducted a study investigating the morbidity and quality of life in former elite Rugby Union players and reported that, compared to the general population sample, Rugby Union players reported significantly higher odds of osteoporosis (Odds Ratio [OR] = 2.69, 95% CI 1.35 – 5.38), osteoarthritis (OR = 4.00, 95% CI 3.32 – 4.81), joint replacement (OR = 6.02, 95% CI 4.66 – 7.77) and anxiety (OR = 2.00, 95%CI 1.11 – 3.61). Furthermore, Hind *et al.* (2020), assessed 189 former Rugby Union and Rugby League players between 2016 – 2018 and reported that, compared to age-matched former non-contact athletes, Rugby players had a twofold greater prevalence of osteoarthritis (51% vs 22%), and were also 2.4 – 9.7 times more likely still feel the impact of their career-related injuries. Rugby players were also 1.7 – 7.3 times more likely to have reported an injury during their careers, particularly at the elite level. Lee *et al.* (2001), also conducted a follow-up study in 1998 on Rugby Union players that had sustained injuries during the 1993–1994 season. Authors reported that 26% of players had to stop playing due to an injury that occurred during their careers, and 9% reported significant negative effects to employment, family life and health. Meir, (1997), suggested that retired Rugby League players with long term injury consequences may experience limited job prospects, diminished income earnings and greater personal medical costs. These findings highlight how important it is to reduce the current risk of sustaining injuries in Rugby Union for player welfare, but recently the consequences of injury have been further exposed.

Injuries acquired during sporting careers can have negative implications on health later in life due to catastrophic and degenerative mechanisms (Webborn, 2012). An area that has gained a lot of attention in sports medicine recently is the neurological impact of repeated concussive injuries. Pearce *et al.* (2018), reported that former professional Rugby League players had significant motor and cognitive deficiencies compared to age match related participants in their study. Furthermore, Hume *et al.* (2017), reported that former Rugby Union players that could recall one or more concussive events had worse "cognitive flexibility, executive functioning, and complex attention", compared to players that did not report a concussive event.

Beyond the player welfare issues associated with Rugby Union, injuries can significantly impact team success also. Williams *et al.* (2015), conducted a 7-year prospective study investigating how team success is compromised by time-loss injuries in elite Rugby Union. There were clear negative associations for team success in relation to injury burden measures (70 – 100% likelihood), and injury burden was shown to hinder competition outcome (i.e., position finished). Furthermore, Starling, (2017), investigated team success in relation to injuries sustained in the Currie Cup Rugby Union competition over a 5 year period. Authors reported that teams in 1st position had significantly lower training and match time loss injuries compared to teams in last position (48 injuries per 1000 hours [95% CI 20 – 76] and 130 injuries per 1000 hours [95% CI 79 - 180], respectively). Furthermore, teams that came in 1st or 2nd place in each season had the lowest injury rates.

Given that injuries have been reported to negatively impact team success, this may also have a large bearing on finical costs and vice versa. At the professional level, there are large financial gains to winning and dominating the major events, particularly in relation to revenue from sponsorships and supporters. On the other hand, greater team success and thus more financial revenue and medical resources may reduce injury risk. For instance, Chalmers *et al*. (2012), previously highlighted in a New Zealand Rugby Union team that injury prevention has much potential, but that substantial resources are required in order to do so. Addressing ground surface hardness and ensuring adequate rehabilitation of primary injuries were two key components for reducing injuries (Chalmers *et al*., 2012). Of course, these changes are more easily achieved by teams who are backed with substantial financial revenue to 'tackle' injury problems. Similarly, a more recent study conducted by Baugh *et al*. (2020), investigated the association between injury outcomes and medical health care in collegiate athletes. Authors combined the National Collegiate Athletic Association (NCAA) Surveillance Program injury data (injury rates, concussion, reinjury, time lost due to injury [days]…) and the NCAA Research sports medicine staffing data, including aspects such as clinicians per athlete and financial data for the sports medicine departments. Baugh *et al*. (2020), reported that schools that had a 1 standard deviation above the average number of clinicians per athlete, had a 9.5% lower rate of injury, 2.7% lower reinjury rate, and a 6.7% lower rate of concussion. In addition, sports medicine groups that were financed by the athletics department, compared to those financed by other departments (when controlling for staffing, sport played, and the division of competition), had a 31% higher incidence of injury. These findings suggests that greater team success (and ultimately greater financial resources), may also aid towards a reduced risk of injury.

Indeed, injured players may require extensive medical and rehabilitation treatment whilst still being paid wages. In such instances, clubs may also have to bring in replacements that require further costs. Consequently, team success may directly impact player injury rates. Similarly, injury rates may also directly impact success and therefore have financial consequences to the team. Ultimately, minimising injury risk without compromising performance is of extreme importance in professional Rugby Union.

In order to minimise the risk of injury in Rugby Union, the injury definitions and methodologies across studies must be replicable in order to fully understand the injury problem. This data can then be used to measure the risk of Rugby Union training and match play, and plan effective strategies to minimise this risk compared to other sports/cohorts. This is further explained in the following sections.

2.4.2 Injury Definition

In Rugby Union, there is a consensus statement for the defining and reporting of injury data to ensure accuracy and consistency across studies utilising the same or similar cohorts (Fuller *et al.*, 2007b). Adhering to these suggestions allows for appropriate comparisons between studies and over time, a more thorough understanding of the injury patterns in Rugby Union. Within the consensus statement for injuries in Rugby Union, injuries are defined as:

'*Any physical complaint, which was caused by a transfer of energy that exceeded the body's ability to maintain its structural and/or functional integrity, that was sustained by a player during a rugby match or rugby training, irrespective of the need for medical attention or time loss from rugby activities. An injury that results in a player receiving medical attention is referred to as a 'medical-attention' injury and an injury that results in a player being unable to take full part in future rugby training or match play as a 'time-loss' injury*.'

Importantly, studies are suggested to not use a mixed definition of injury (Fuller *et al.*, 2007b), and in Rugby Union, a more inclusive >24 hour time-loss injury definition is suggested to be best practice (Fuller *et al.*, 2007b). The consistency with using a 24 hour time loss definition has vastly improved the reporting of injuries for studies in Rugby Union following consensus statements (Williams *et al.*, 2013).

2.4.3 Injury Incidence

When reporting injury data, using methods that taken into account the degree of exposure players have acquired in training and match scenarios is important. One of the most well established injury reporting tools in Rugby Union is injury incidence (Brooks *et al.*, 2005, 2005a, 2005b, 2006a, 2008, Fuller *et al.*, 2008, 2012, 2016; West *et al.*, 2019). Although there are various ways of reporting incidence, in Rugby Union, calculating injuries as per 1000 hours of training or match exposure is the most common (Fuller *et al.*, 2007b). Incidence rates per 1000 hours accounts for exposure diversity between players/teams and thus allows comparisons between studies of the same and different sports. Importantly, the use of injury incidence over other methods of reporting injury data is considered good practice, as although the proportion of injuries may remain the same, say for example, from season to season, the incidence may change significantly based on that player's or team's relative level of exposure (Fuller *et al.*, 2007b). For example, Fuller and colleagues, (2008, 2012, 2016), used injury incidence to standardise injury findings over the 2007, 2011 and 2015 Rugby World Cups (RWC). Match injury incidence was reported as 83.9/1000 player-match hours in 2007, 89.1/1000 player-match hours in 2011 and 90.1 match injuries/1000 player-match hours in 2015, highlighting a steady increase in Rugby Union match injury rates over time. Conversely, the authors reported training injury incidences of 3.5/1000 player-training hours in 2007, 2.2/1000 player-training hours in 2011, and 1.0 training injuries/1000 player-training hours in 2015, indicating a clear decline in training injury rates over the same period. These findings alone would suggest that the match demands in elite Rugby Union are increasing; likely due to improved player monitoring and injury reduction strategies employed in a more controllable training environment, which has correspondingly reduced training injury rates.

Studies of a longer magnitude, however, have shown limited variation in both training and match injury rates. Williams *et al.* (2017b) , who collected training and match data over a similar time period (2006/07 - 2012/13 seasons) to Fuller *et al.* (2008, 2012, 2016), reported a mean training injury incidence of 2.8 (± 0.4) per 1000 hours of training (and comparable match injury rates of 85.9 (± 9.0) per 1000 player match hours) over 7 seasons. Furthermore, a study conducted by West *et al.* (2019), who assessed the influence of training volume over 11 elite Rugby Union seasons, reported a training injury incidence of 2.6/1000 player-hours (95% CI: 2.4 to 2.8), suggesting injury rates have not declined in elite Rugby Union over the last decade.

The interpretation and comparability of literature assessing team sport injury risk has improved through the use of standardised collection and analysis tools. Injury incidence not only allows researchers to evaluate and compare the risks of same-sport studies in multiple settings, but also for interpreting where other sports sit in comparison. When reporting the incidence of injury in Rugby Union, it is good practice to report training and match data separately. This is because training accounts for ~ 89 - 95% of total exercising exposure in the elite setting (Fuller *et al.*, 2008; Fuller *et al*., 2012; Kemp *et al.*, 2016), thus reporting training and match incidence values together could mask the high incidence rates often reported from competition (Brooks and Fuller, 2006; Fuller *et al.*, 2007b).

2.4.4 Injury Severity

Beyond reporting the incidence of injury, injury severity is an important tool for assessing the resulting time (days) lost from training or competition injury. In the Rugby Union consensus statement, injury severity is defined as:

"*The number of days that have elapsed from the date of injury to the date of the player's return to full participation in team training and availability for match selection*."

The Rugby Union consensus statement also recommends reporting the degree of injury severity as: slight (0-1 days), minimal (2-3 days), mild (4-7 days), moderate (8-28 days), and severe (>28 days). Similar to injury incidence, the use of accurate and consistent methods for reporting severity data allows injury patterns to be seen over time. For instance, West *et al.* (2019), showed that over 11 seasons of data collection, the mean severity of training injuries rose in all but two seasons. This suggests that the severity of training injuries may have increased over time in Rugby Union, with the 2017/18 season reporting the highest severity values (37 days per player injury (West *et al.*, 2019). In addition, the severity of injuries can be reported between training activities to highlight the potential risks of different training types. For example, West *et al.* (2019), reported gym-based training had the lowest mean injury severity. Similarly, Brooks *et al.* (2008), also reported gym-based training to have the lowest severity following a 2-season analysis of 11 English Premiership Rugby Union teams.

As well as reporting injury severity means, the median severity (calculated as the range midpoint of injury severity data) is an important value to present in published literature (West *et al.*, 2019). Median values can show the effect that a small number of high severity injuries can impose on mean severity values (West *et al.*, 2019). For example, in the 2017/18 season, when West *et al.* (2019), reported mean severity to be at its highest (37 days), median severity was less than half the mean value (17 days). Furthermore, Fuller *et al.* (2017), who assessed the incidence and severity of injuries over the World Rugby's 2014/15 and 2015/16 annual Sevens World Series (SWS), as well as the 2016 Rio Olympics, reported mean severity values of 41.3 (36.2 to 48.1), 39.0 (29.3 to 47.1) and 86.0 (38.4 to 133.6) in the men's tournaments, respectively. This was compared to median values of 28 (22 to 33), 21 (17 to 26) and 40 (17 to 234) over the same tournaments. The reporting of mean and median values when assessing injury data in team sport athletes is therefore imperative to fully understand the injury data presented.

2.4.5 Injury Burden

When providing injury incidence and severity data, it is important to also provide the overall burden of an injury. Injury burden can be used for identifying which injuries result in the greatest loss of time, and which injury factors are thus most important for preventing future occurrence (Fuller, 2018). Given that injury burden is a product of incidence rate (the probability that an injury occur as a result of participating in a given activity) and mean severity (consequence) of that given injury (Fuller, 2018), and is usually presented as absence/1000 player-hours. This data can be presented via tables or graphs with the incidence and severity values also to reflect which injury factors influence player availability over time (Fuller, 2018;

West *et al.*, 2019). For example, players with high severity values, but low incidence rates may show similar burden values to high incidence, low severity injury players, but the influence of high severity players being out for extended periods of time may have a more negative impact on overall team performance and success, particularly if those players are considered to be 'key, high play ability' players (West *et al.*, 2019).

2.4.6 Summary

When collecting and reporting injury data in team sports like Rugby Union, the design and methodological approaches adopted can produce conflicting or incomparable results unless the definitions and methods used are consistent and accurate across the literature. The publication of a consensus statement for Rugby Union based studies has minimised inconsistencies and allowed for comparable results that accurately establish the extent of the impact of injuries in professional Rugby Union. This has been considerably beneficial for researchers and practitioners alike.

2.5 QUANTIFYING WORKLOAD-INJURY RELATIONSHIPS VIA CONTEMPORARY PRACTICES OF PLAYER LOAD MONITORING

2.5.1 Training Volume

Training volume is an easily measured, simplistic and reliable tool for monitoring external training load in Rugby Union players, yet there is a relatively small number of studies that have explored the association between volume (hours of training) and injury risk in this cohort (Brooks *et al.*, 2008; Viljoen *et al.*, 2009; West *et al.*, 2019). Previously, Brooks *et al.* (2008), reported that professional Rugby Union players averaged 6.9 (± 3.5) player-hours per week of training in a season. Similarly, West *et al.* (2019) reported a mean volume of 6.8 (95% CIs: 6.5 – 7.1 hours) player-hours per week over an 11-season study. Both Brooks *et al.* (2008), and West *et al.* (2019) reported that pre-season training volumes were considerably higher than in-season training volumes (9.2 hours vs. 6.3 hours and 9 hours vs. 6 hours, respectively). Previously, this has been suggested to be due to the higher levels of conditioning performed in the pre-season period to prepare players for the competitive demands of match play throughout the in-season period. Accordingly, this is associated with a switch from gym-based training to more on-pitch work as player's transition from the pre-season to the in-season period, which may be coupled with a greater injury risk. Indeed, although West *et al.* (2019), reported July and August (the main portion of pre-season training) to have the highest training volumes compared to all other months of the season, injury incidence was lower in these months due to the much lower injury risk associated with gym-based training compared to on-pitch work (Gannon *et al*., 2016; West *et al.*, 2019). In addition, Windt *et al.* (2016), reported that greater pre-season participation decreased the likelihood of injury throughout the competitive season in Rugby League players, whereas Murray *et al*. (2017a), reported that greater pre-season training loads were positively associated with a greater tolerance for higher in-season load and player match availability. Such findings suggest that players who are exposed to higher training workloads early in the season may be better equipped to deal with the high demands of competitive match play in contact team sports. Nevertheless, it cannot be ignored that players who are able to cope with higher training loads, whether this be early season or throughout the season, may simply be the healthiest players on the team. Indeed, Cresswell and Eklund, (2006), who investigated burnout in professional Rugby Union players in New Zealand reported that most players believed that the short off-season break (players are typically allowed one-month) is not long enough to physically and mentally recover from the preceding season, let alone prepare for the upcoming season. Inadequate breaks between seasons were associated with ill-prepared players entering the following season still carrying injuries from the year before (Cresswell and Eklund, 2006). Therefore, these players would simply not be able to train at a higher level during the pre-season, which will ultimately add to a lack of preparation and a higher risk of injury in the in-season phase. These players may also be at an increased injury risk when exposed to training volumes they are not prepared for.

When investigating overall training volume Brooks *et al.* (2008), reported that intermediate training volumes (6.2 – 9.1 hours per week) resulted in the lowest number of days lost due to injury, whereas higher training volumes (> 9.1 hours per week), increased the severity of match injuries. It is important to note that the weekly volumes reported by Brooks *et al.* (2008), were not mean training volumes per player throughout the season, but rather, the fluctuation in training volume on any given week. Therefore, increases in 'acute' training volume (1-weekly periods) may induce greater training fatigue and, in turn, increase the potential for a more severe injury outcome. Indeed, similar findings for acute increases in volume have been reported previously. Brooks *et al.* (2006b), reported that hamstring injury rates were greater when training volume the week before match play was higher. Furthermore, Viljoen *et al.* (2009), previously reported that Rugby Union players had a slight reduction in in-season injury rates over a 3-season period when training volume was reduced. However, it is important to note that the teams involved also dropped from 3rd to 7th (2002-2004). Thus, players may have been exposed to inadequate training loads to elicit the physiological adaptations needed to compete effectively during match play. Indeed, Ball *et al.* (2018), reported that higher weekly training volume in the Backs was associated with significantly lower match incidence rate ($p = .007$). Therefore, exposing players to appropriate training volumes may improve player resilience and protect against injury risk.

2.5.2 Match Exposure

Qualitative research conducted previously by Cresswell and Eklund, (2006), highlighted the growing concerns associated with player burnout through the relentless demands placed on professional Rugby Union players to compete in the high number of matches throughout a season. A large proportion of Professional Rugby Union players play for multiple teams during a season and consequently must adhere to various coaching strategies, training structures and match tactics. Within the study conducted by Cresswell and Eklund's, (2006), players reported that transitioning between competitions was the most stressful part of the season due to the short recovery periods between matches and the high expectations placed on these players who are paid to win games. Players perceived that there was an ‘anti-rest’ culture in professional Rugby Union, and felt that they were expected to play in every game of the season due to the ethos that comes with competing at the professional level (Cresswell and Eklund's, 2006). Indeed, players regarded this as unrealistic given the number of matches in a season. Increased match exposure is coupled with more frequent and greater contact loads due to the sophisticated nature of strength and conditioning practices to optimise player performance in the modern era.

Previously, Phibbs *et al.* (2018), reported perceived player-loads (sRPE) to considerably increase over 2-week periods when match frequency was increased. In addition, Carling *et al.* (2017), previously highlighted the consequences of exercise-induced fatigue due to congested Rugby Union fixtures. Under 20 Rugby Union Back players who were exposed to >75% of the tournament and > 75 minutes in the final 3 matches reported moderate-to-large decreases in total and high metabolic load distance. In addition, Forwards showed similar reductions for high-speed distance. Indeed, excessive match exposure may be coupled with both a physical deterioration in performance due to match-induced fatigue, which also results in greater player perceived demands and emotional exhaustion. Although the aforementioned studies were conducted using adolescent players, a seven season study conducted by Williams *et al.* (2017b), showcased the potential negative effects of both high and low match exposure in a professional Rugby Union cohort.

The reported findings by Cresswell and Eklund's, (2006), prompted a quantitative approach adopted by Williams *et al.* (2017b), to investigate the risks associated with match exposure in professional Rugby Union. Authors assessed the risks of match exposure in two ways. Firstly, the injury risk associated with 12-month match exposure (number of games involved in [> 20 minutes] in the preceding 12-month period) was investigated; secondly, the injury risk associated with 1-month match exposure via full-game equivalents (FGEs, number of games involved in over the preceding 30 days, calculated as the total minutes played divided by 80) was investigated. Authors reported a non-linear relationship with match exposure and injury risk over a 12-month period. Players exposed to less than 15 or more than 35 matches over 12-months were most susceptible to injury. On the other hand, increases in 1-month match exposure was linearly associated with an increased injury risk, particularly for players with low chronic match exposure over a 12-month period (Williams *et al*., 2017b). Indeed, such findings have practical applications in Rugby Union structuring and help inform coaches and practitioners of potential player match-boundaries in relation to injury risk. Nevertheless, this study was conducted using English Premiership teams, and therefore these findings cannot be generalised to all Rugby Union cohorts. An important point of consideration when using volume/exposure to investigate load however, is that these methods fail to consider the intensity of training and match play, which have previously been associated with both an increased and reduced injury risk in team sports (Cross *et al.*, 2016; Gabbett, 2016a; Colby *et al.*, 2017a, 2017b; Gabbett and Whiteley, 2017; Murray *et al.*, 2017c; Stares *et al.*, 2018; Cummins *et al.*, 2019; Bowen *et al.*, 2020). Currently, the association between external training load and injury risk remains unknown in professional Rugby Union, at least to the author's knowledge.

2.5.3 Training and Match Load Measures as Risk Factors for Injury

Training and match load have been highlighted as modifiable risk factors for injury within contact team sports. Previously, a number of well-established indices of training and match load have been derived from various loading variables (e.g., sRPE, GPS, IMU devices), and have shown strong associations with injury risk. Therefore, the aim of this section of the literature is to provide an overview of these load indices and to highlight the key findings presented from previous research (see Table 2.2).

Table 2.2: Training and match load measures, definitions and calculations.

Training and Match Load Variables	Description	Calculation
Daily load	Sum of training load for all sessions completed in one day	The total load for all session summed in a day (e.g., if a player completed two pitch-based training sessions at 2000 m and 1500m, their daily load for total distance would be 3500 m)
Weekly load	The total load a player was subjected to over a weekly period	Calculated by summing a player's daily load from the previous 7 days (week commencing on a Monday)
Week-to-week change in load	Absolute difference between the current week's total load and the previous week's total load.	Sum of the current week's load is subtracted from the sum of the previous week's load.
1,2,3, and 4 week cumulative loads	Sum of total training load for the previous 7, 14, 21 and 28 days.	1, 2, 3, and 4-week rolling loads accumulated over 7, 14, 21 and 28 days.
Acute: chronic workload ratio (ACWR [rolling coupled])	A player's most recent 1-week load (acute workload) and their previous 4-week rolling average (chronic workload) is expressed as a ratio to inform injury risk.	Acute (rolling 7-day) workload is divided by chronic (previous 28-day rolling) workload.
Acute: chronic workload ratio (rolling uncoupled)	A player's most recent 1-week load (acute workload) and their previous 3-week uncoupled rolling average (chronic workload) is expressed as a ratio to inform injury risk.	Acute (uncoupled rolling 7-day) workload is divided by chronic (previous 21-day uncoupled rolling) workload.
Acute: chronic workload ratio (EWMA)	Compared to the rolling average method, the EWMA model is suggested to better represent the variations in which load is accumulated. The model assigns a decreasing weighting factor for each older workload value, which is suggested to more accurately represent an athlete's current load status by accounting for the decaying nature of fitness, and the non-linear nature of injury occurrence and workload.	To begin the EWMA ACWR calculation, the first load value in the series was recorded as the average of the first 7-days load. Thereafter the EWMA for a given day is calculated by: $EWMA_{today} = Load_{today} \times \lambda_a + ((1 - \lambda_a) \times EWMA_{yesterday})$ Where λ_a is equal to the degree of decay and given by: $\lambda_a = 2/(N + 1)$ N is the chosen time of decay (7 or 28 usually for acute and chronic, respectively). The value on day 28 – for example - is the ACWR for that given period. Finally, the EWMA acute workload is divided by the EWMA chronic workload (Williams *et al.*, 2016; Murray *et al.*, 2017b).

Workload spike	A rapid increase in a player's acute training load.	A workload spike is represented by an acute: chronic workload ratio of 1.5 or above.
Chronic workload status	A player was considered to be in a high chronic loading state if they were equal to or above the median split based on the chronic part of the ACWR calculation. A player was considered to be in a low chronic loading state if they were below the median split	Calculated by taking the median score for each players positional chronic load

Previously, research has shown the utility of using these loads measures to help inform potential injury risk factors in Rugby Union. Using the sRPE method, Cross *et al.* (2016), investigated the following workload measures: 1) weekly load 2) week-to-week change in load, 3) 2-, 3- and 4-week cumulative loads and 4) the traditional ACWR method (a player's acute [one week] workload divided by their chronic [four week rolling average] workload) over the in-season phase of a season, in which 173 professional Rugby Union players were involved. Cross *et al.* (2016), reported that 1-week loads and week-to-week changes in load reported a linear relationship with increased injury risk, with a 2 standard deviation (SD) increase in these variables (1245 and 1069AU, respectively). Authors reported odds ratios (OR) of 1.68 (95% CIs: 1.05 – 2.68) and 1.58 (95% CIs: 0.98 – 2.54) for these variables, respectively. Furthermore, over 4-week cumulative periods, a significant non-linear 'U-shaped' relationship was reported with injury risk. Authors reported that an intermediate 4-week load (5932 – 8651AU) was associated with a likely beneficial reduction in injury risk (OR = 0.55, 95% CIs: 0.22 – 1.38), whereas high 4-week cumulative loads of > 8651AU reported a likely harmful effect (OR = 1.39, 95% CIs: 0.98 – 1.98).

An important metric in recent studies assessing workload and injury risk is the use of ACWRs. The ACWR is useful as it presents information on what the athlete has previously been exposed to, compared to what the athlete is currently undertaking. This is particularly important when analysing the influence of external load on injury risk, given that external load is suggested to be a poor marker of fatigue (Windt and Gabbett, 2016). The use of ACWRs allows coaches and practitioners to understand where each athlete is in terms of current intensity, and the influence that reducing this or going above it may have on injury risk. For instance, a high ACWR (e.g., 1.5) indicates that the athlete has been exposed to loads that are substantially greater than what their recent previous training has prepared them for, whereas a low ACWR (e.g., 0.8) indicates the athlete has been exposed to loads lower than what they have previously been prepared for. Nevertheless, Cross *et al.* (2016) found no relationship between the traditional ACWR measure and injury risk. There are numerous papers highlighting the potential inadequacy of this measure to accurately represent the realistic nature of load and recovery and consequently, the utility of the traditional ACWR to measure the influence of load on injury risk. The use of weekly rolling averages to measure, the influence of chronic load (i.e., 'fitness') and acute load (i.e., 'fatigue') on injury risk may be inappropriate since the physiological adaptations associated with exercise training 'do not fit averages' (Menaspà, 2017). As previously shown by Dr Menaspà, rolling averages can overlook variations within, for example, the commonly used 4-week period, despite stark variations in daily load patterns. The rolling method also fails to account for when that exposure occurred in relation to when that athlete would have recovered from the given stimulus (Menaspà, 2017). Using daily calculations, the variations from day-to-day can be seen for rolling calculations compared to the weekly measures (see Figure 2.12A and 2.12B for comparison). The ACWR is the same over the given period, but more information on the daily fluctuations in load is provided. Nevertheless, this measure still fails to consider the decaying nature of fatigue and the importance of recovery. A previous paper published by Williams *et al.* (2016), provided a more realistic and sensitive measure for calculating ACWRs. This calculation uses an exponentially weighted moving average (EWMA) to provide a more sensitive ACWR score than the rolling method (see Figure 2.12C).

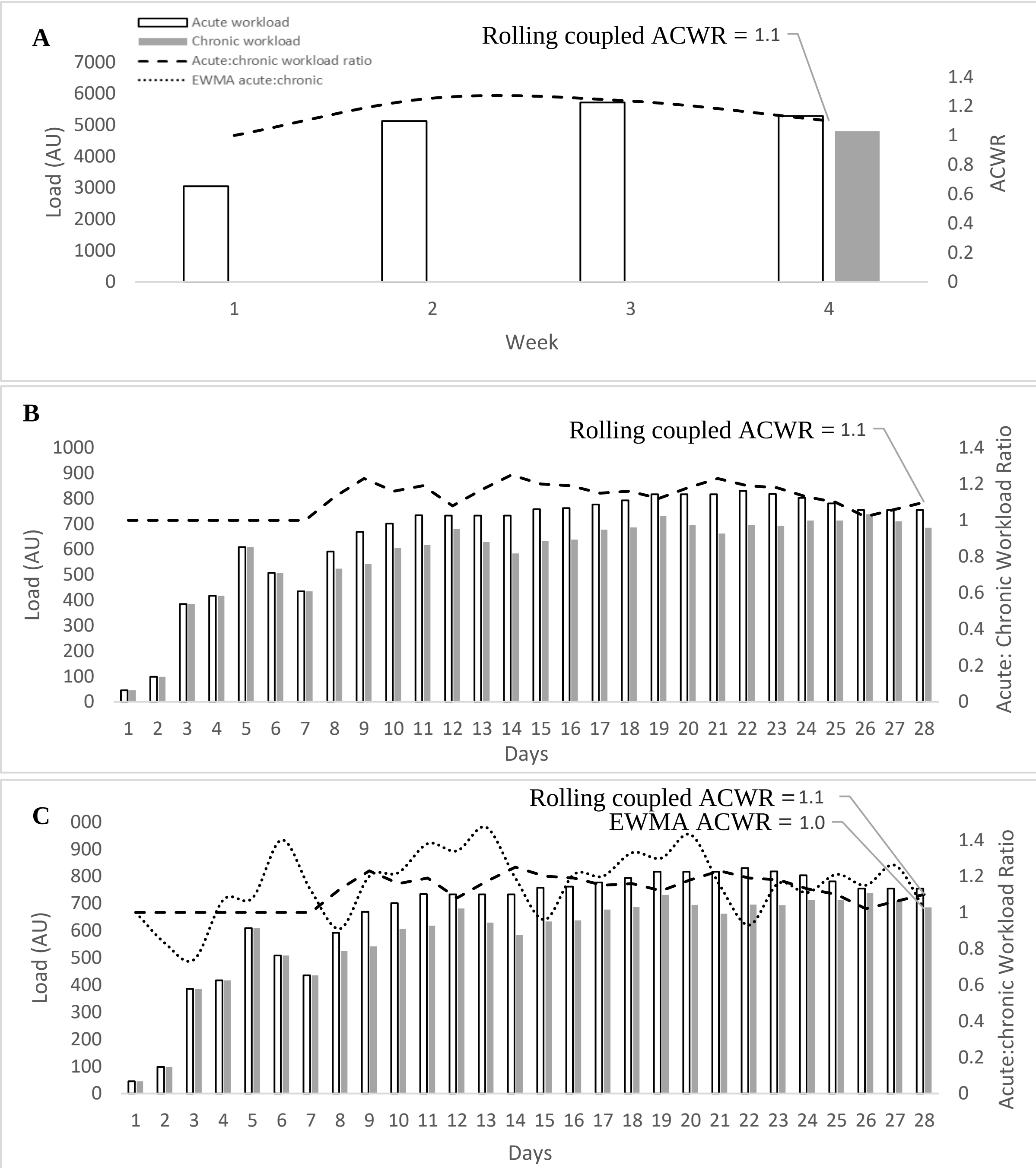


Figure 2.12: Weekly and daily rolling coupled acute: chronic workload ratios with the EWMA acute: chronic workload ratio for comparison.

NOTE: AU, arbitrary units; EWMA, exponentially weighted moving average; ACWR, acute: chronic workload ratio; white bars, acute load; grey bars, chronic load; dashed line, rolling coupled ACWR; dotted line, EWMA ACWR.

The use of rolling averages means a training session completed at the start of the chronic period (i.e., week 1) is equally as weighted as a training day carried out the day before the ACWR analysis (i.e., week 4). The use of the EWMA approach mitigates this limitation by giving a greater weighting to higher loads undertaken towards the end of the, e.g., 28 day period. Therefore, when modelling the relationship between load and injury, the EWMA ACWR produces a more appropriate loading index (Williams *et al.,* 2016). Indeed, the use of this method to monitor loads and inform injury risk in team sport has been reported to be a more useful and sensitive measure (Williams *et al.*, 2016; Murray *et al.*, 2017b).

Beyond the EWMA ACWR, other methods have also been proposed to calculate ACWRs for injury risk assessment. Using the traditional 1-week (acute) vs. 4-week (chronic) ACWR may result in mathematical coupling due to a spurious correlation between acute and chronic load estimates (Lolli *et al.,* 2017). When calculating the chronic load, the acute load represents a term in this part of the calculation:

$$\frac{A}{0.25 * (A + W2 + W3 + W4)}$$

*'A' = the acute (current weekly) volume/load. The chronic load values are then calculated using A, W2 (preceding 2^{nd} week), W3 (preceding 3^{rd} week) and W4 (preceding 4^{th} week).

Thus, the calculation does not distinguish between the acute and chronic elements, resulting in the coupling of these functions which in turn, alters the ACWR and provides a biased and invalid metric (Lolli *et al.,* 2017). Authors also reported trivial within-subject correlations between the two elements of the calculation, and reported large and inverse within-subject correlations between the ACWR and its chronic load denominator (Lolli *et al.,* 2017). However, a simple approach to preventing this is simply to remove the acute element of the calculation out of the chronic, and thus remove associations between the two calculations (Lolli *et al.*, 2017). The formula for this is given below:

$$\frac{A}{0.3333 * (W2 + W3 + W4)}$$

*'A' = the acute (current weekly) volume/load. Chronic volume/load is then calculated using W2 (preceding 2^{nd} week), W3 (preceding 3^{rd} week) and W4 (preceding 4^{th} week).

The utility of this calculation to inform injury risk in team sport has been shown (Lolli *et al.*, 2017; Bowen *et al.*, 2020), and is arguably the more appropriate method when using rolling data to calculate injury risk from loading parameters.

The use of the aforementioned calculations (Table 2.2) has previously shown strong associations with injury risk. Another important calculation recently explored in the literature is a player's chronic workload status in relation to their ACWR. Similar to appropriately high cumulative loading (Cross *et al*., 2016), it has been shown that appropriate high chronic loading may mediate the risk of injury (Malone *et al.*, 2016, 2018; Gabbett *et al.*, 2016a). Acute and overwhelming increases in absolute load, or relative load compared to what the athlete was prepared for however, has shown significant associations with an increased injury risk in multiple team sports (Bowen *et al.*, 2017; Cross *et al.*, 2016; Cummins *et al.*, 2019; Malone *et al.*, 2017c; Murray *et al.*, 2017b; Rogalski *et al.*, 2013).

Therefore, players who have acquired appropriate high chronic loads may be more protected against injury when exposed to high ACWRs (Malone *et al.*, 2017c). Contrary to high loading conditions however, an inadequate training/match stimulus will hinder adaption and the force-loading capacity of musculoskeletal tissue, thereby increasing injury risk (McIntosh, 2005; Colby *et al.*, 2017a; Williams *et al.*, 2017b). Therefore, a low chronic workload status coupled with a high ACWR may increase injury risk. This is particularly important in team contact sports where the majority of injuries are a result of contact events (e.g., tackling, rucking, scrummaging, wrestling etc.). Therefore, assessing the ACWR during periods of low or high chronic loading may provide an appropriate approach for investigating the possible risk of injury for acute vs chronic loads in relation to what the athlete has previously performed.

These workload measures have been used numerously in recent team sport load monitoring studies investigating injury risk. Therefore, the aim of the following section (2.5.4) is to provide a detailed analysis of how external workload variables have been used to track and monitor workload, and how these calculations have been used in conjunction with this data to present a comprehensive evaluation of how training and match load may influence injury risk in team sport.

2.5.4 Global Positioning Systems and Inertial Measurement Units

Historically, the monitoring and testing of athletes was performed in laboratory settings where external factors such as the environment or the intensity of exercise could be controlled

(Larsson, 2003). Using machines such as treadmills or cycle ergometers, athletes could remain quasi static, allowing tethered electronic implementation (i.e., gas analysers or cameras) to measure metabolic or locomotive characteristics that cannot be used in a training or match environment. With advancements in modern day technology however, athletes can now use unobtrusive devices that monitor player loads in sport-specific settings (Cunniffe *et al.*, 2009; Cahill *et al.*, 2013). Two of the most commonly used, and fundamentally important tools for tracking player loads in contact (and non-contact) team sports is the use of GPS devices housing IMU technology.

Over the years, advancements in GPS technology have allowed wearable devices to be commercialised for sports teams wanting to monitor athletes during training sessions and competitive match play. The Australian Institute of Sport and the Cooperative Research Centre first pioneered the use of GPS devices in team sport over a decade ago. Two of the researchers launched Catapult Sports (Catapult Sports, Canberra, Australia) after developing accurate devices using southern hemisphere Rugby teams. Now, devices have been reduced in size, making them more comfortable and safer to wear, vests have been re-designed to minimise movement of the device and provide more accuracy, and the technology has much greater sampling frequencies (e.g., 10 Hz a second), compared to initial devices (e.g., 1Hz) (Akenhead *et al*., 2014; Buchheit *et al*., 2014; Jennings *et al.*, 2010).

Similar to GPS devices, advancements in microelectromechanical systems (MEMS) - used to build various systems, including accelerometers, gyroscopes, and magnetometers - have allowed for the creation and implementation of inertial measurement units in various applications (Aughey, 2011). For example, in the automobile industry IMUs are used to deploy airbag systems when a crash is detected; in clinical exercise settings, IMUs can be used to assess gait characteristics, and in elite sport, IMUs can assess exercise intensity through accelerations/decelerations, impacts from tackles or total PlayerLoad^{TM} (Gabbett, 2015; Phibbs *et al.*, 2016; Varley *et al.*, 2012).

The IMUs used in elite sports monitoring comprise of at least two sensors: accelerometers for linear motion and gyroscopes for angular motion. By summing the measurements over a given period of time, an IMU can determine instantaneous position, orientation, velocity and the direction of movement of a travelling object (James, 2006). Linear and rotational motion can be measured over three perpendicular axes (linear = surge, heave, and sway; rotational = roll, pitch, and yaw). Together, these units yield a measure of six degrees of freedom (DOM) that can define the specific movements of a person over time (Chambers *et al.,* 2015; Hulin *et al.*, 2017).

The data derived from accelerometers provide the majority of statistics used by coaches and sport scientists to assess performance. Accelerometers recognise the magnitude and direction of vibrations during exercise and convert these vibrations to digital recordings measured in gravitational force (G-force) (Halsey *et al.*, 2011). This can be achieved through the micro-electrical crystals within accelerometers, which are sensitive to the gravitational pull of the earth (Halsey *et al.,* 2011). The magnitude of impact forces during exercise, such as contact events in Rugby Union, are recorded by accelerometers and multiplied by the mass of i.e., a player, to give the force output according to Newton's second law (i.e., force = mass x acceleration). The use of such data can be used to monitor the intensity of training and match play in Rugby Union (i.e., a high number of collisions may suggest a player was subjected to a high intensity during training/match play) (Roe *et al.*, 2016b).

Beyond assessing the isolated load of single risk factors (e.g., single plane accelerations only), the overall load a player was subjected to during training or match play can be calculated via a vector magnitude referred to as PlayerLoad™ (Aughey, 2011). PlayerLoad™ is an external load monitoring tool thought to provide coaches with the overall load placed on an individual during training or competition (Aughey, 2011). The PlayerLoad™ algorithm is sensitive to exercising activities completed in all planes (i.e., vertical, medial-lateral and anterior-posterior), such as quick changes of direction, collisions, or running during Rugby Union match play. PlayerLoad™ is described as an 'instantaneous rate of change of acceleration' by the manufacturers, and has become a common measure of external load in Rugby Union. In fact, the use of PlayerLoad™ in team sport began through a collaborative project between Catapult and the Australian Institute of Sport to measure the overall load of Rugby Union.

One of the most practically important aspects of GPS housing IMU devices for monitoring player load in team sport is the ability to investigate both training and match play scenarios. Objective measures of internal load are often used to represent a player's stimulus for adaptation following exercise (Impellizzeri *et al.*, 2004), and are thus important for assessing player load. However, such measurements are rarely permitted in competition. The use of GPS and IMU devices have thus become common practice for monitoring athlete's external loads in training and competition. The ability of these devices to track team and individual player movement patterns during training and match play, has allowed coaches and practitioners to further understand the overall demands associated with team contact sports (Cahill *et al*., 2013; Cunniffe *et al.*, 2009; Reardon *et al*., 2015; Tee *et al*., 2015).

When investigating load-injury relationships, the aforementioned workload measures (see Table 2.2) have been used across multiple team sports in conjunction with modifiable external workload variables derived from GPS devices to investigate injury risk. Yet, to the researcher's knowledge, there have not been any studies investigating the influence of these workload measures (derived through GPS/IMU devices) to inform injury risk in elite Rugby Union. In other team contact sports, the potential injury risks associated with GPS and IMU derived loads have been reported. For instance, in elite Australian Football, Colby *et al.* (2014), reported that players with very high 3-weekly cumulative loads for total distance (TD), sprint distance and force load were significantly more likely to be injured compared to the reference group. Similarly, Murray *et al.* (2017c), reported that high acute (1-week) loads for PlayerLoad^{TM} significantly increased injury risk in Australian Footballers. In Rugby League however, Cummins *et al.* (2019), reported that high 4-week PlayerLoad^{TM} (>3800 AU) and total distance (> 60,000m) was associated with a decreased injury-risk in the subsequent week. In addition, Cummins *et al.* (2019) reported that very-high speed distance was associated with an increased injury risk, whereas high-speed running was not. Beyond absolute speed zones, Murray *et al.* (2018), used relative speed zones to investigate injury risk in Australian Football. Authors reported that injury risk was increased (relative risk = 2.26) for slower players when they were exposed to greater absolute high-speed chronic workloads, whereas injury risk was reduced (relative risk =0.33) for the same players when they were exposed to greater relative high-speed chronic workloads. Authors also reported that high and very-high speed running zones were significantly underestimated for absolute running speed zones compared to relative thresholds for slower players. In Rugby Union, Weaving *et al.* (2018), previously carried out a principal component analysis and highlighted that GPS (total distance [TD] and individualised high-speed running distance [>61% maximal velocity]) and IMU (PlayerLoad^{TM}) measures could account for the variation in external load. Authors showed that TD reported a PC_L of 0.86 to 0.98 and PlayerLoad^{TM} reported a PC_L of 0.71 to 0.98 for the 1st PC. In addition, in support of findings presented by Murray *et al.* (2018), on the utility of relative high-speed measures, Weaving *et al.* (2018), reported that individualised high-speed running distance was the only variable to relate to the 2nd PC (PC_L: 0.72 to 1.00), and captured additional load information (+19 – 28%).

Beyond contact team sports, Bowen *et al.* (2017), reported low 1-weekly TD significantly reduced injury risk in professional Soccer players. In addition, Bowen *et al.* (2020), also investigated the impact of chronic loading and the ACWR (rolling uncoupled) on injury risk. Authors reported that injury risk was significantly reduced when all chronic loads were combined, and the ACWR was low for total distance (ACWR = 0.4–0.7). However, contrary to a reduction in injury risk, the authors also reported that injury risk was highest when chronic exposure to decelerations were low (<1731) and the ACWR was >2.0 (RR=6.7). In addition, injury risk was also 5-6 times higher when chronic exposure to accelerations was low (<1881) and the ACWR was >2.0 (RR=5.4– 6.6).

Similar findings have also been reported in contact team sports. Colby *et al.* (2017b), reported that elite Australian Football players with a low chronic distance coupled with a very high distance ACWR had an increase injury risk compared to players with an above average chronic load coupled with a moderate ACWR. Furthermore, in a similar cohort, Murray *et al.* (2017b), reported that injury risk was significantly increased (players were 5 – 21 times more likely to be injured) when players were exposed to an ACWR > 2, compared to an ACWR between 1 – 1.49 for TD, HSR distance and player load. In Rugby League, Hulin *et al*. (2016b), reported that high chronic workloads (>16 095m) were combined with a very- high 2-week average ACWR (≥ 1.54) elicited the greatest risk of injury. Interestingly, these findings suggest that high chronic loading combined with a high ACWR may also increase injury risk beyond the commonly reported 'low chronic vs. high ACWR' relationship. Indeed, similar to excessive cumulative loading, high chronic loading may increase athletes' susceptibility for injuries if the load is not systematically and gradually increased. Therefore, injury risk may actually be increased, and further exasperated by a high ACWR when chronic loads are high.

The aforementioned findings have provided important consideration for coaches and practitioners involved in elite contact team sport. However, all sports have specific stimuli and independent risk factors that may not translate from sport to sport. Therefore, given that there is a lack of research in this area in elite Rugby Union, conducting an investigation into the possible risk factors associated with GPS and IMU derived load via workload calculations (e.g., acute, chronic, weekly changes, cumulative loading) could provide important practical applications for load monitoring and injury reduction strategies.

2.5.5 Player Position

Beyond simply measuring the load of training and match play scenarios, investigating the position specific stimuli and stress associated with each player's role is important in Rugby Union. Playing position is one of the most easily identified, non-modifiable risk factors in Rugby Union and it is well established that position specific differences exist. For instance, Roberts *et al.* (2008), reported that throughout Rugby Union match play, Backs covered more distance than Forwards (6127 m vs. 5581m, respectively), which is a well-established finding in other Rugby Union studies (Cunniffe *et al.*, 2009; Cunningham *et al.*, 2018; Lindsay *et al.*, 2015; Reardon *et al.*, 2017b). Authors (Roberts *et al.*, 2008) reported that, although much of this was simply due to greater walking distances (2351 m vs. 1928 m, respectively), Backs also covered significantly more high-speed running distance (448 m vs. 298 m, respectively), which has also been reported numerous times previously (Cunniffe *et al.*, 2009; Lindsay *et al.*, 2015; Pollard *et al.*, 2018; Reardon *et al.*, 2017b). Roberts *et al.* (2008), reported that Forwards spent a significantly greater percentage of time engaging in high-intensity activities (11.5% vs. 3.8%), of which many were static, isometric contraction type events (e.g., scrummaging, rucking, and mauling). Indeed, during Rugby Union match play, it is well established that Forwards engage in more impacts than Backs (Duthie *et al.*, 2003; Howe *et al.*, 2017; Quarrie *et al.*, 2013). Noteworthy, is that Roberts *et al.* (2008), reported no differences between time spent in different match play activities between Forwards positions (tight vs. loose Forwards). However, Back Row Forwards have previously been reported to engage in more tackles and perform higher acceleration and deceleration loads (James *et al.*, 2005; Jones *et al.*, 2015; Lindsay *et al.*, 2015). Owen *et al.* (2015), reported that the greatest number of impacts were endured by the Front Row Forwards, and the lowest number of impact were sustained by the inside backs in Rugby Union (Owen *et al.*, 2015).

Even with distinct differences between positional groups however, Williams *et al.* (2013), previously reported that the differences in incidence and severity between Forwards and Backs were likely trivial (76% and 80% likelihood). Indeed, as suggested by Williams *et al.* (2013), this similar risk profile may be linked to improved conditioning strategies, thereby narrowing the workload gap between players (Quarrie and Hopkins, 2007). Nevertheless, even if the injury risks between positions are similar, the differences attributing to these high injury rates are likely associated with very different training and match demands. Therefore, although positional groups are often combined for analysis in Rugby Union studies due to statistical power reasons (Cahill *et al.*, 2013), this may mask the individual differences between positions, which would likely provide coaches and practitioners with a more sound understanding of how these individual loads placed on players result in high injury rates across the board. Therefore, the investigation of position-specific load-injury relationships via contemporary load-injury measures and calculations may improve injury prevention strategies in the elite Rugby Union setting.

When investigating positional differences and player workloads in general, the methods adopted will considerably influence the findings reported. For instance, Howe *et al.* (2017), investigated the demands of professional Rugby Union via 10 Hz GPS devices with integrated IMUs sampling at 100 Hz (Optimeye S5, Catapult Sports, Melbourne, Australia). Authors reported that investigating positional differences via GPS units only (instead of using a combination of GPS and IMU measures) would have resulted in a considerable underestimation of the workload performed by Forwards, due to the more contact and discrete work performed by these players. Howe *et al.* (2017), reported that PlayerLoad^{TM} per unit of distance covered was higher in Forwards than Backs, likely due to engaging in more contact events, and being exposed to more total work during match play - a finding that would not have been picked up by GPS units alone. In line with this conclusion, Roberts *et al.* (2008), who previously investigated the positional demands of professional Rugby Union match play, reported that Forwards perform longer duration bouts of discrete high-intensity activity and also perform significantly more bouts (for longer periods) of static exertion compared to Backs. Roberts *et al.* (2008), concluded that these findings were attributed to Forwards engaging in scrums, as well as performing more rucks, mauls and tackles

2.5.6 Video Analysis and Coding

Similar to the additional information that can be provided by IMUs compared to GPS analysis alone, there is a vast amount of information that can also be provided via video analysis methods compared to IMU data only. A limitation of IMU devices is that they fail to account for high-intensity static exertions such as scrummaging. In addition, although IMUs have been reported to accurately identify collision events in contact team sports (Hulin *et al.*, 2017), they have also been reported to inaccurately classify a number of movement actions as collision events also (e.g., quick accelerations or changes of direction). Indeed, a Rugby Union study conducted by Kelly *et al.* (2012), who investigated the automatic detection of micro-technology to identify impacts, previously reported difficulty when assessing the accelerometer signals to identify collision events. This was due to peaks in acceleration data resulting from a multitude of movement actions that are often not impact related (e.g., jumping, running, falling etc.) Furthermore, Clarke *et al*. (2017), previously investigated the ability of micro-technology to distinguish between contact-related impacts and non-contact events in Rugby Sevens. Authors reported that these impact events were inaccurately coded between 45 and 62% of the time. Thus, micro-technology can severely overestimate the number of impacts a player was exposed to during match play. Indeed, Cunniffe *et al.* (2009) previously investigated the demands of professional Rugby Union and reported that (via accelerometer data) a single Forward and Back sustained 1274 and 798 impacts, respectively. In addition, Venter *et al.* (2011) previously assessed the movement demands and impacts in under-19 Rugby Union match play. Authors reported that Forwards sustained impact counts of 858 per game compared to 830 for Backs. These impact counts are well above the impacts reported using more reliable methods such as video coding analysis.

Using video coding analysis, Roberts *et al.* (2008), reported that Forwards and Backs averaged 89 and 24 impacts per game. Furthermore, Fuller *et al.* (2007a), previously conducted a two-season study (2003/04 and 2005/06) which involved 645 professional Rugby Union players and reported that tackles were the most common event during match play, in which 221 events occurred per game. Furthermore, Kelly *et al.* (2012), conducted a preliminary investigation in their study and reported that, in over 18 test matches in international Rugby Union over 2 seasons (2009 – 2011), players engaged in a mean of 138.28 tackles per game. Although higher than the number of events reported by Roberts *et al.* (2008), this is still well below the impacts presented by Cunniffe *et al.* (2009) and Venter *et al.* (2011) using accelerometer based methods. Indeed, these findings support previous statements by Reardon *et al.* (2017a), in which authors compared micro-technology devices to video analysis methods for coding collision events in Rugby Union, and reported that when using micro-technology to detect contact events, there may be 'substantial overestimation or underestimation' compared to when using video analysis methods.

Accurately investigating the demands of Rugby Union match play via video coding methods can provide important information with regards to the loads and risks associated with different events. For example, Fuller *et al.* (2007a), reported that tackles resulted in the greatest days lost (701.6 days lost per 1000 player hours), but that scrummaging and collision events resulted in the highest risk per event (213.2 days lost per 1000 player hours and 199.8 days lost per 1000 player hours). Furthermore, using video analysis methods, Fuller *et al.* (2010), previously reported that ball carriers and tacklers were at a significant injury risk for the following scenarios: 1) when the impact force of tackles were high; 2) the player entered the tackle at a high speed 3) the player was hit around the head/neck area or 4) the player was involved in a collision. Beyond just the movement actions of the events, repeated tackling can result in excessive loads that may increase player fatigue and ultimately injury risk. Usman *et al*. (2011) previously reported that the amount of shoulder force a player could produce (via an active shoulder tackle into a 45kg tackle bag with an incorporated force plate) was decreased following repeated tackling in Ruby Union. Authors attributed this lack of force production to tackle-induced fatigue, which has also been associated with a reduction in tackling technique in Rugby League players (Gabbett, 2008), and a greater risk of injury. A visual representation of how Rugby Union impacts may influence injury risk is provided by Hendricks and Lambert, (2014) (see Figure 2.13). Authors provided an important overview of the injury risk factors associated with contact events, which was theorised based on previous modelling by McIntosh, (2005). Indeed, injury risk (particularly in contact team sports) is caused by an overload of the system's tolerance levels (i.e., a collision that would overwhelm even the most conditioned player's stress-bearing capacity) or through repeated exposure to load (e.g., tackles) that reduces the system's tolerance levels to such a degree that 'normal loads' cannot be tolerated (Hendricks and Lambert, 2014).

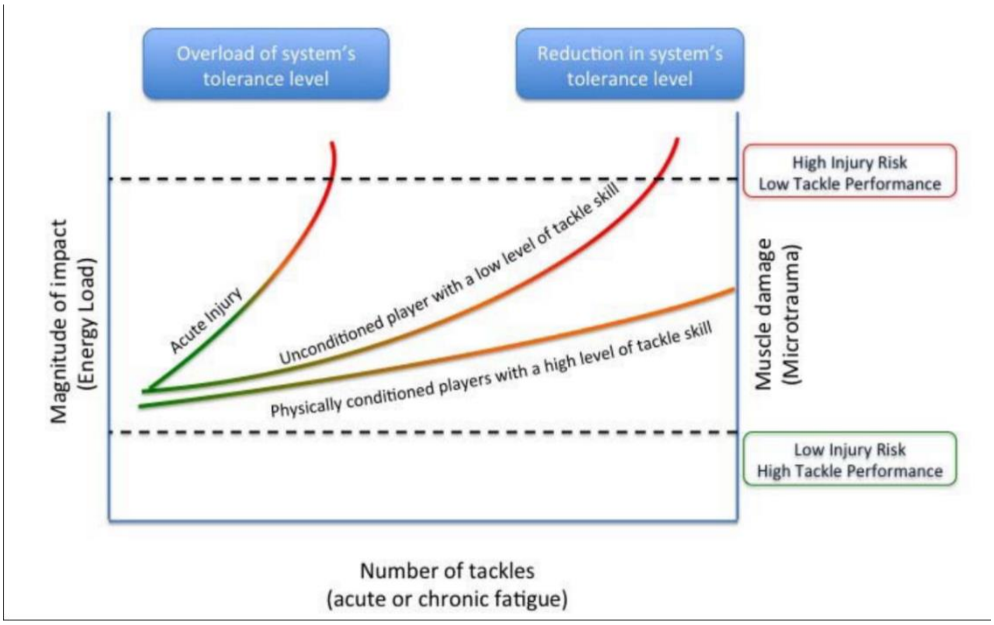


Figure 2.13: Theoretical model describing the relationship between tackles engaged in (acute or chronic), tackle impacts (energy load), muscle damage (micro trauma) and tackle injury risk (tolerance reduction/overload and performance.

This theoretical model highlights the relationship between contact exposure, (acute or chronic fatigue), the magnitude of that contact exposure (energy load), and the resultant muscle damage, all which interact with injury risk (tolerance over- load or reduction) and performance. This relationship is likely to differ depending on the position in which a player plays, as it is well-established that the number and nature of contact events differ depending on playing position (Quarrie and Hopkins, 2008; Fuller *et al.*, 2010). Therefore, providing important findings regarding the demands and injury risks associated with contact events in Rugby Union at the positional level may further develop our understanding of how contact loads implicate injury risk and player performance.

2.5.7 Summary

There are a number of well-established workload measures that can be used to monitor player workloads and quantify the injury risks associated with Rugby Union training and match play. The methods adopted in previous studies to track workload data are vast and depending on the approaches used, different risk factors may be presented. Previously, risk factors such as training or match volume (hours), match exposure (number of matches involved in), GPS and IMU derived loads (e.g., total distance, high speed running, accelerations, PlayerLoad^{TM}), as well as video coding methods to report collision loads have been used in Rugby Union. In addition, positional differences have been presented, which highlight the importance of looking at workloads at the positional level, and not just for the overall team. Through the use of these methods we can further develop our understanding of how Rugby Union related workloads influence injury risk, and such information can be used by coaches and practitioners to optimise player preparation, performance development and ultimately, player welfare.

2.6 RESEARCH RATIONALE

This chapter provides an overview of the methods and continued developments that have been employed by coaches, practitioners and researchers alike to accurately and reliably measure training and match loads in Rugby Union - and comparable contact team sports – in relation to performance and injury risk. The evolution of athletic performance modelling has improved our understanding of the influence of workload on player injury risk; injuries in professional Rugby Union (particularly time-loss) are one of the highest in all professional team sport settings (Williams *et al.*, 2013), and this can have an overwhelming impact on team performance, and consequently success, which in turn places a large burden on player welfare (Williams *et al.*, 2015). Given that external workload is an inevitable part of professional Rugby Union, investigating this workload-injury relationship is important for improving performance and ultimately injury risk and player welfare. Indeed, to some degree, the greater the workload exposure, the greater the injury risk. Nevertheless, external workload is a modifiable risk factor, and it is well understood that an appropriate and well-structured training programme that accounts for the demands of match play and fixture congestion, whilst also considering recovery and exercise-induced adaptations can reduce injury risk and protect players from inappropriate changes in external workload (Quarrie *et al.*, 2016; Soligard *et al.*, 2016; Windt and Gabbett, 2016).

As per the workload sink analogy, the response associated with the training and competition stress and stimuli an athlete is exposed to (e.g., improved performance or injury) is directly influenced by their current physical capacity to tolerate and recover from that given workload. Developing resilient athletes who are able to tolerate high workloads and remain injury free takes time, and must consider appropriate scientific strategies. The aim is to enhance our understanding of how training and match workload can both increase and reduce injury risk depending on how the given workload dose is applied. A deeper understanding of this process in professional Rugby Union will ultimately improve player welfare. Nevertheless, this is a complicated process. In order to achieve these aims, a number of important aspects must be considered. For instance, the methodology adopted, in terms of data collection, cleaning, storage and ultimately the data and statistical analysis approach used will have a large influence on the results presented. In turn, this directly impacts the strategies and decision making of coaches and practitioners working in the elite setting. In addition, the definitions used and whether these adhere to consensus statement recommendations will have a large bearing on the generalisability of the results presented, and consequently the utility of the findings in the elite team sports setting.

From a comprehensive analysis of previous literature, a number of well-established workload measures have been identified. Previously, training and match volume (hours), and match exposure (number of matches involved in) have been shown to influence injury risk in elite Rugby Union. Data presented from these studies has provided a foundation on which other Rugby Union cohorts can build upon and further develop these aforementioned findings.

In addition, team contact sports have previously looked at multiple loading injury risk factors, such as cumulative loads, weekly fluctuations in load or variations in ACWRs (Cross *et al.*, 2016; Gabbett, 2016a; Colby *et al.*, 2017b; Murray *et al.*, 2017b; Malone *et al.*, 2017b, 2017c; Cummins *et al.*, 2019). The majority of these studies have derived these workload calculations from sRPE or GPS/IMU data. However, one of the most easily collected, accurate and modifiable measures of external workload is training volume. Given that training volume has clearly been linked to training and match injury previously (Brooks *et al.*, 2006b, 2008; Cummins *et al.*, 2019; West *et al.*, 2019), attention regarding the use of this metric via these well-established loading measures should be considered also. Indeed, in Rugby League Cummins *et al.* (2019), previously reported that as the ACWR increased above 1.00, so did injury risk when using volume. This however, to the researcher's knowledge, has not been investigated in Rugby Union. Furthermore, although workload calculations are often derived from GPS and IMU data, this has – to the researcher's knowledge - not been investigated in Ruby Union either. Indeed, Cross *et al.* (2016), previously showed that acute and cumulative loads were associated with injury risk in Rugby Union via the sRPE method. Therefore, using similar (and more recent) workload measures via GPS and IMU data could provide important considerations for the planning and implementation of training and match loads in elite Rugby Union players. Given the clear positional differences in Rugby Union, assessing this at the positional level is also important.

CHAPTER 3

Understanding the Match and Training Volume-Injury Relationship in Elite Scottish Rugby Union

3.1 INTRODUCTION

Rugby Union is a physically demanding intermittent sport which requires players of all positions to engage in repeated bouts of high intensity exercise interspersed with periods of low intensity activity (Roberts *et al.*, 2008). Given all players are exposed to both contact and running demands, a well-developed periodised training programme must be in place if players are to elicit training-induced adaptations that prepare players for the demands of match play (Johnston *et al.*, 2014a; Gabbett, 2016a). In order to elicit these adaptations, players are often exposed to increases in either training volume (hours spent training) and/or intensity (e.g., progressive overloading through lifting heavier weights/increasing the number of sets previously performed/completing running drills at a greater running velocity/engaging in more contact work…) (Campbell *et al.*, 2017). Monitoring the direct impact of alterations to training volume and/or intensity on performance and player injury risk is therefore important (Campbell *et al.*, 2017). For example, if the acute training stimulus is too low, then the desired physiological adaptations needed to cope with Rugby Union match play will not be acquired. Contrarily, if the training stimulus is too high and players are not given appropriate recovery time, then fatigue may set in and injury may ensue (Campbell *et al.*, 2017).

A well-designed training programme needs to be multi-factorial and incorporate various modalities such as strength training, aerobic conditioning, high intensity interval training, and skill sessions (Tee *et al.*, 2016; Gannon *et al.*, 2016; Campbell *et al.*, 2017). However, some coaches may simply increase player training volume (hours) in an attempt to elicit training induced adaptations (Brooks *et al.*, 2008). When structured inappropriately, training volume has been linked to increased training injury incidence and match severity in contact teams sports (Gabbett, 2004a; Gabbett, 2004b; Brooks *et al.*, 2005, 2005b; Brooks *et al.*, 2006b). Indeed, higher training volumes may result in excessive external loading, in turn placing high biomechanical strain on the muscles, joints and connective tissue of the athlete’s involved. Given the internal loading on the musculoskeletal system cannot be directly measured however, external risk factors like training and match volume provide surrogate measures to monitor injury-load relationships in training and match play scenarios (Cummins *et al.*, 2019).

Studies have attempted to prevent or even predict training and match injuries through the investigation of multiple training and match load related injury-risk factors (e.g., low or high workloads, poor recovery, workload spikes) (Cummins *et al.*, 2019). The majority of these studies have focused on accumulated workloads, week-to-week changes and/or variations of a players acute: chronic workloads (ACWR) through numerous loading factors (i.e., sRPE, GPS-derived running and contact measures or volume) (Rogalski *et al.*, 2013; Cross *et al.*, 2016; Williams *et al.*, 2016; Gabbett, 2016a; Hulin *et al.*, 2016b; Colby *et al.*, 2017b; Murray *et al.*, 2017b, 2017c; Malone *et al.*, 2017b, 2017c; Fanchini *et al.*, 2018; Cummins *et al.*, 2019). Findings from these studies have shown that higher accumulated workload periods may protect players from injury, whereas acute increases in load (i.e., spikes, often assessed via the ACWR) or large fluctuations in weekly load often precede an injury (Rogalski *et al.*, 2013; Cross *et al.*, 2016; Gabbett, 2016a; Gabbett *et al.*, 2016a). Furthermore, multiple studies assessing cumulative workloads and ACWR measures have reported a U-shaped relationship between workload intensity and injury risk, such that intermediate-high workloads have shown reduced injury risk, whereas very low and very high workloads increased injury risk (Cross *et al.*, 2016; Gabbett, 2016a; Malone *et al.*, 2016; Malone *et al.*, 2017b). The methods employed to monitor these workloads have also been heavily debated (Williams *et al.*, 2016; Menaspà, 2017; Lolli *et al.*, 2017, 2019; Impellizzeri *et al.*, 2019, 2020). For instance, it has been suggested that authors should use more sensitive measures when using ACWRs to investigate injury, such as daily measures and the exponentially-weighted moving average (EWMA) (Menaspà, 2017; Williams *et al.*, 2016). Whereas, when using weekly calculations, it has been suggested that authors avoid coupled rolling methods that may cause spurious correlations (Lolli *et al.*, 2017). The large majority of these studies have focused on the intensity risk factors of training and match play (Rogalski *et al.*, 2013; Cross *et al.*, 2016; Williams *et al.*, 2016; Gabbett, 2016a; Hulin *et al.*, 2016b; Colby *et al.*, 2017b; Murray *et al.*, 2017b, 2017c; Malone *et al.*, 2017b, 2017c; Fanchini *et al.*, 2018). As far as the author is aware, no studies have used these well-established loading monitoring tools to investigate the influence of training volume on injury risk in elite Rugby Union. There are benefits to using training volume (hours). For example, player adherence does not come into question and thus cannot influence the quality of the data, as may be the case when monitoring load via the commonly used Session Rating of Perceived Exertion (sRPE) method. Furthermore, there are numerous papers highlighting the inadequacy of GPS devices to measure higher-intensity movements during training and match play (Coutts and Duffield, 2010; Jennings *et al.*, 2010; Johnston *et al.*, 2014b; Macfarlane *et al*., 2015), and accuracy issues surrounding IMU derived measures, such as accelerations and decelerations (Buchheit *et al.*, 2014; Thornton *et al.*, 2019). Consequently, the use of training and match volume may be one the most simplistic and safe-guarded measures when investigating the workload-injury relationship in elite team sports.

Beyond training volume, simply evaluating the number of Rugby Union match exposures (the number of games a player was exposed to) over acute (30-day) and chronic (12-month) periods have shown both linear and non-linear associations with injury risk. Williams *et al.* (2017b) reported that players who had been involved in < 15 or more than > 35 matches had a greater injury risk compared to intermediate-high exposure, whereas monthly match exposure was linearly associated with injury risk. These findings suggest that both training and match volume can have major implications on training and match injury risk if exposure levels are sub-optimal. Consequently, training and match injury incidence, severity and burden have previously been investigated in various forms, such as weekly, monthly and seasonal splits, as well as time spent in different training types (e.g., on-pitch based work vs. gym-based work).

The aim of this study was to investigate the influence of training and match volume (hours) and exposure (numbers of competitive games played) on training and match injury risk in elite Rugby Union. The hypotheses for elite Rugby Union players in this study were: (1) players with higher mean weekly training volume would be protected against injury risk (i.e., that a negative linear relationship between volume and injury risk would exist); (2) a U-shaped relationship for match 12-month exposure would exist; and (3) that daily ACWR calculations would be better able to detect injury risk compared to weekly calculations for training volume.

3.2 METHODOLOGY

3.2.1 Study Design & Participants

This is a 2-year prospective observational epidemiological study assessing the influence of training and match volume (volume = hours of training or match play) and match exposure (exposure = number of individual match involvements) on injury risk in elite Scottish Rugby Union (SRU) players. First team players contracted to the SRU's professional men's 15-a-side teams (Glasgow Warriors, Edinburgh Rugby and Men's International Squad) were involved in this study. Training and match data were recorded for all individual player positions and SRU positional groupings (See Table 3.1).

Table 3.1: Player positions, Scottish Rugby Union's positional grouping categories and main player groupings.

Number	Player Position	SRU Positional Groupings	Main Grouping
1	Loose-head Prop	Prop	Forward
2	Hooker	Hooker	Forward
3	Tight-head Prop	Prop	Forward
4	Lock	Second Row	Forward
5	Lock	Second Row	Forward
6	Blind-side Flanker	Back Row	Forward
7	Open-side Flanker	Back Row	Forward
8	Number 8	Back Row	Forward
9	Scrum-Half	Scrum-Half	Back
10	Stand Off	Stand Off	Back
11	Left Wing	Back 3	Back
12	Inside Centre	Centre	Back
13	Outside Centre	Centre	Back
14	Right Wing	Back 3	Back
15	Fullback	Back 3	Back

Data were collected from a total of 163 players (27.3 ± 4.3 years, 103.5 ± 12.2 kg) across the 2017/18 and 2018/19 seasons. Eighteen players were not contracted to Edinburgh Rugby or Glasgow Warriors and were therefore excluded from the data analysis, leaving 145 individual players. Eighty-six players (59%) were involved in both seasons (46 forwards; 40 backs). A total of 32 players (17 forwards; 15 backs) were involved in the 2017/18 season (22%), and 27 players (18 forwards; 9 backs) were involved in the 2018/19 season (19%). In total, 231 individual player-seasons were captured over the study period.

3.2.2 Ethical Approval

The Edinburgh Napier University Ethical Committee, in accordance with the 1964 Helsinki declaration and its later amendments or comparable ethical standards, approved all procedures and protocols. The SRU granted access to all player load measures monitored, and injury data collected by the SRU teams involved in this study. Data were collected from all players contracted to the SRU, who had agreed for their data to be used for research purposes as part of their professional contracts. Management, medical and performance staff also granted formal permission to collect all data used in this study. Data relates to training and match volume and exposure information collected via player GPS devices with in-built IMUs and all gym-based information collected via team weights-logs and team ratings of perceived exertion (RPE) databases.

3.2.3 Data Collection for Training and Match Volume and Exposure

3.2.3.1 Pitch-Based Training, Match Volume and Exposure Data Collection

All pitch-based training, match volume and exposure data were collected via GPS devices housing IMU technology. All teams used Catapult's Optimeye S5 devices for outdoor training sessions and match play except Edinburgh Rugby, who used GPSports EVO devices for the 2017/18 in-season phase (as previously mentioned in Chapter 3A). For the 2018/19 season, all teams used Catapult's Optimeye S5 devices for outdoor sessions, and Catapult's ClearSky T6 units for indoor sessions.

For pitch-based data collection, all GPS units were switched on to establish a clear satellite connection prior to the commencement of each training session or competitive match. Players were then fitted with their designated GPS unit prior to the commencement of the warm up. Team coaches and practitioners thereafter ran through the planned training session for that day. On completion of each training session, the data was downloaded on the appropriate cloud (Catapult or GPSports), manually adjusted for the start and end of the training session, and exported to a CTR file on Excel (Version 16; Microsoft, 2016). The SRU team coaches and practitioners associated with their club recorded all data for each training session and competitive match. Each team kept a record of all raw training and match CTR files. In addition, each team had their own unique GPS database that was used for player monitoring purposes. During weekly meetings at Murrayfield Stadium, the researcher acquired the up-to-date raw CTR exports, as well as the latest version of each teams own unique GPS database.

These were cross-checked at every instance to ensure all player training sessions and competitive match involvements were included in this study.

3.2.3.2 Gym-Based Training Volume Data Collection

Gym-based training volume data were recorded by team coaches and practitioners associated with each team on Google Docs. Within this file, the following information was used: the date of the training session; the player who performed the training session; the gym-based session type (e.g., "Lower Body Weights", "Upper Body Weights" or "Full Body Weights") and each player's training session volume (see Table 3.2 for example). This file was known as each team's 'RPE database'. *Noteworthy, is that each team's RPE database did contain RPE data (Borg's Modified CR-10 scale, Borg, 1998), however, these databases were only used to extract accurate gym-based training volumes as shown in Table 3.2. The RPE data was not used - and is therefore not referred to - in this study.* In addition to the RPE database, each team used a team weights-log spreadsheet on Microsoft Excel (Version 16), which provided the individual exercises performed by each player, as well as the load (weight) and repetitions performed for the given exercise (see Table 3.3 for example). Player session type (e.g., "Upper Body Weights"), as well as the training session volume (e.g., 45 minutes) were not provided in the weights-log database. The team RPE databases were thus considered the 'gold-standard' when collecting gym-based training volume data, as these databases provided more accurate information (i.e., a training volume category). When data were missing from team RPE databases, the weights-log data was used to estimate training volume.

Table 3.2: Example of some of the data provided to monitor gym-based training volume from team RPE databases.

Player	Date	Day	Week Number	Session Type:	Training Volume (Minutes)
A	04/06/2018	Monday	1	Upper Body Weights	45
A	04/06/2018	Monday	1	Lower Body Weights	30
B	04/06/2018	Monday	1	Full Body Weights	60
C	04/06/2018	Monday	1	Full Body Weights	60
D	04/06/2018	Monday	1	Upper Body Weights	45
D	04/06/2018	Monday	1	Upper Body Weights	15
E	04/06/2018	Monday	1	Full Body Weights	60

Table 3.3: Example of some of the weights-log data used to categorise session type (exercise data) and estimate training volume (load and rep data).

Player	Date	Exercise	Load	Reps
A	04/06/2018	Squat	100	5
A	04/06/2018	Shoulder Press	40	5
B	04/06/2018	Paused DB Bench	128	8
C	04/06/2018	Eccentric Bench Press	160	2

3.2.3.3 Gym-Based Training Data Sources

The data sources used to collect gym-based training volume are provided in Table 3.4. Over the 2017/18 season all of Edinburgh Rugby's gym-based training data were taken from the Edinburgh RPE database (i.e., the 'gold standard' for training volume). For Glasgow Warriors, the RPE database was used in combination with the Glasgow Warriors weights-log over the 2017/18 season. For Scotland International, the training volume data were taken from a number of platforms over the 2017/18 season. These included Scotland's Autumn Test, Six Nations and Summer Tour RPE databases; the Scotland International training camp data, Autumn Test and Six Nations training schedule Spreadsheets and EDGE 10. All of these sources (for Scotland International) provided accurate training volume data for each gym-based training session. Over the 2018/19 season, team RPE databases were used for all teams. Where there were sessions in team weights-log databases that were missing from team RPE databases, the weights-log data was used to estimate training volume for those sessions.

Table 3.4: Data sources and platforms used to collect gym-based training data over the 2017/18 and 2018/19 seasons.

Season	Team	Data Sources	Platform Used/Exported to
2017/18 Season	Edinburgh Rugby	Edinburgh Rugby RPE Database	Microsoft Excel
2017/18 Season	Glasgow Warriors	Glasgow Warriors RPE Database / Glasgow Warriors Weights-log	Microsoft Excel
2017/18 Season	Scotland International	Scotland International RPE databases / Scotland Training Schedule Spreadsheets / Scotland Training EDGE 10 Data	Microsoft Excel
2018/19 Season	Edinburgh Rugby	Edinburg Rugby RPE Database / Edinburgh Rugby Weights-log	Microsoft Excel
2018/19 Season	Glasgow Warriors	Glasgow Warriors RPE Database / Glasgow Warriors Weights-log	Microsoft Excel
2018/19 Season	Scotland International	Scotland International RPE Database	Microsoft Excel

3.2.4 Data Cleaning and Storage for Training and Match Volume and Exposure

3.2.4.1 Player Coding

On collection of training and match data, unique player codes were created for each individual to ensure players could not be identified within any team database. Player codes were password protected, and only the researcher had access to these codes. Player codes were consistent across all databases and seasons where any data was stored. This meant that cross checks between different databases and data combining could be achieved with ease. It also allowed player data to remain anonymous when going through multiple files. Positions were also formatted so that they were the same across all teams, (e.g., “Lock” was updated to “Second Row” so that all Second Row players could be assessed within and between teams).

3.2.4.2 Player Exclusion

When collecting training and match data, any player who was not training or playing at the professional level were discarded and thus were not used for analysis purposes. In addition, any player who was not 18 or over was also excluded.

3.2.4.3 Duplicates

Duplicates (i.e., a data entry with the same player code, date, training activity, and training volume) throughout all datasets were identified and removed where appropriate. Duplicates were checked with a sports scientist at the SRU for potential removal. In instances where a player had completed a non-weight bearing return to play (RTP) session, or light conditioning, the sessions were kept, as these sessions were often completed in short intervals multiple times per day.

3.2.4.4 Producing Gym-Based Training Session Types for Gym-Based Sessions

When a gym-based training session was noted in a team's weights-log but not in the RPE database, the weights-log data was used to estimate training volume. The weights-log did not give the session type (e.g., "Upper Body"). Therefore, prior to estimating the volume of these training sessions, basic coding was performed in Microsoft Visual Basic to categorise weights-log sessions. The formula to achieve this is shown below:

"=TRAININGANALYSIS([@Date],[Date],[@Player ID],[Player ID],[Weights Category])"

The formula works by looking up the date of the training session, the player who completed the training session, and the weights category for each exercise (Table 3.5 provides examples of how the exercises performed translate to a given weights category, which is then looked up by the formula to pull back an accurate session type, e.g., "Full Body Weights").

Table 3.5: Example of using weights-log exercises to create training session types.

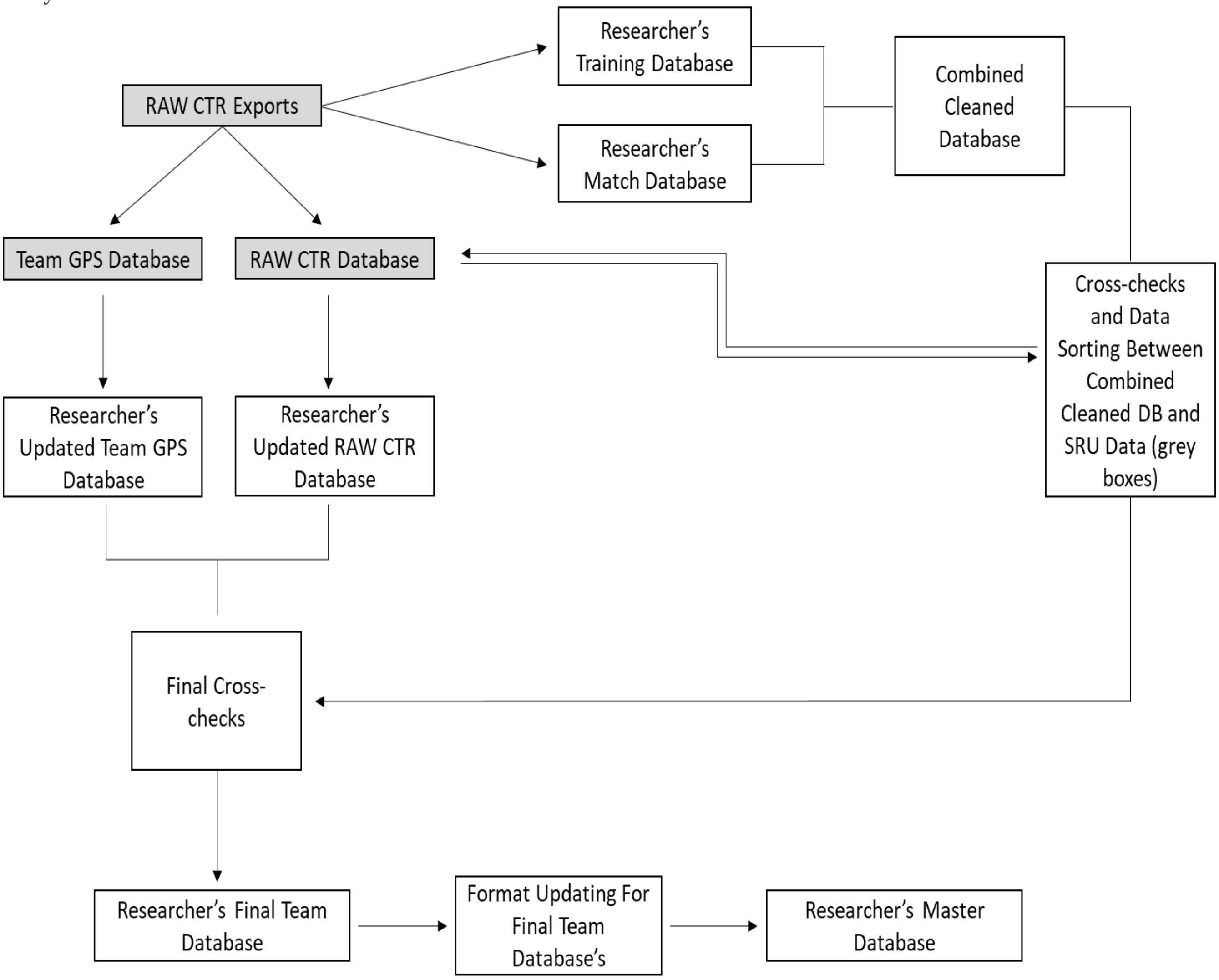
Player	Exercise	Weights Category	Session Type
A	Squat	Lower Body Weights	Full Body Weights
A	Shoulder Press	Upper Body Weights	Full Body Weights
B	Paused DB Bench	Upper Body Weights	Upper Body Weights
C	Ecc Bench Press	Upper Body Weights	Upper Body Weights

3.2.4.5 Data Cleaning for Global Positioning System and Gym-based Volume Data

The raw CTR exports - using Microsoft Excel and Microsoft Power BI (Power BI Pro, Microsoft, 2019) - were used to collect all pitch-based training and match volume data. A unique database was set up on excel for each team. This was done separately for pitch-based training and match play data (i.e., a training database and a match database). Training and match databases were then combined to provide a cleaned team database for each season (e.g., "Edinburgh Rugby 2017/18 Database"). These databases were cross-checked with the raw data provided by the SRU (Raw exports, team GPS databases and CTR databases, see Figure 3.1), so that any data missing in either database was noted and corrected. Further cross-checks were then carried out on each of the researcher's 'updated' cleaned databases to ensure all training sessions and match data were accounted for by using a SUMIFs calculation. Days with > 10 % difference were further evaluated. Differences were then rectified to ensure all data were accurate. Once all training and match dates had been corrected, final data checks were conducted by randomly selecting 10% of the data from each month. If any discrepancies were found across the databases, then all of that data for that entire month was re-analysed and rectified. The data was considered adequately and appropriately safeguarded against human error once all checks had been completed. The finalised database for each team and each season were then produced in one format, so that one master database, encompassing all training and match volume data, was produced (See Figure 3.1 for a simplified flow chart of the process, and Table 3.6 for the master database format).

Separate databases were also constructed for the gym-based training data for each team and season. All collected data was cross-checked for each team between their independent weights-log database and RPE database (except Scotland International, as they did not use a weights-log). On completion of these cross checks, a combined gym-based training database was created in the same format as the GPS database. All of the gym-based training data were then combined and added into the master database.

Figure 3.1: Flowchart of the processes taken to ensure data accuracy for the Master GPS Database used in this study.



NOTE: Grey filled boxes indicate data taken from the SRU, white boxes indicate the researcher's databases and data sorting.

Table 3.6: Central database column titles and descriptions.

Column Title	Description
Database	Separate databases were combined into one master document. The database categories included: "Match Play"; "On-pitch Training"; "Weights & Off-feet Conditioning"; "Pre-match Warm-up".
Season	All data sets were sorted into the correct season via "Season 1 (2017/18)" or "Season 2 (2018/19)" descriptions.
Taken From	Depending on where the data had been taken from (e.g., RAW CTR files, team GPS databases, video footage, team weights-logs, team RPE databases), each row was given an appropriate label so that all data could be easily identified in raw files for the correct team (i.e., instead of 'team database', the row would say 'Edinburgh Rugby's Weights-log', for example).
Team	The team the player is assigned to (e.g., Glasgow Warriors or Edinburgh Rugby)
Current Environment	The environment the player is training or playing in (e.g., an Edinburgh Rugby assigned player playing for Scotland International).
Player ID	The ID assigned to the player (specific codes created by the researcher for every player so that names could not be identified)
Period Name	The name assigned to the training session/match by the team coaches (e.g., Fitness Testing; Rugby; Units; Rehab; Return to Play Conditioning; Speed Session etc.).
Training/Match Type	Details of whether it was a training session or competitive match (i.e., Training; Match Warm Up; Pre-Season Friendly; PRO 14 Match; Challenge Cup (European); Champions Cup (European); Autumn Test Match (International); Six Nations Test Match (International); Summer Tour Test Match (International)).
Date	The date of the training session
Day	The day of the training session
Week	The week of the training session (week beginning on a Monday)
F/B	Whether that player played as part of the Forwards or Backs
Position	The players individual/preferred playing position (Loose-head Prop, Tight-head Prop, Hooker, Lock, Open-side Flanker, Number 8, Blindside Flanker, Scrumhalf, Stand-Off, Centre, Wing, Fullback)
SRU Positional Groupings	The players positional group (Prop, Hooker, Second Row, Back Row, Scrumhalf, Stand Off, Centre, Back 3)
Start Time	Start of the training session for 2018/19 data.
End Time	End of the training session for 2018/19 data.
Duration (hours)	Duration of time the player spent training or competing in match play ([h]:mm:ss)
Field Time (hours)	Duration of time the player was competing in match play ([h]:mm:ss)
Volume (minutes)	Volume of each training session/match completed in minutes (calculated from duration x 1440).
Volume (Decimal)	Volume of training or match play in decimals.
Actual/ Estimated	Whether the data was recorded by the GPS unit or had to be estimated
Duplicates	Duplicate calculation was run on excel to identify extra data that may have been added intentionally or not intentionally
Comments	A comments column was added so that changes to the database could be tracked, and adjusted data could be identified

3.2.5 Quantifying Training and Match Volume

3.2.5.1 Pitch-Based Training Volume

Training was defined as "*Team-based and individual physical activities under the control or guidance of the team's coaching or fitness staff that are aimed at maintaining or improving players' rugby skills or physical condition*". (Fuller *et al.*, 2007b). Training volume was defined as the *"total training time, from commencement of the warm up until the training session was deemed complete by the training staff, including water breaks and/or breaks between drills* (See Figure 3.2).

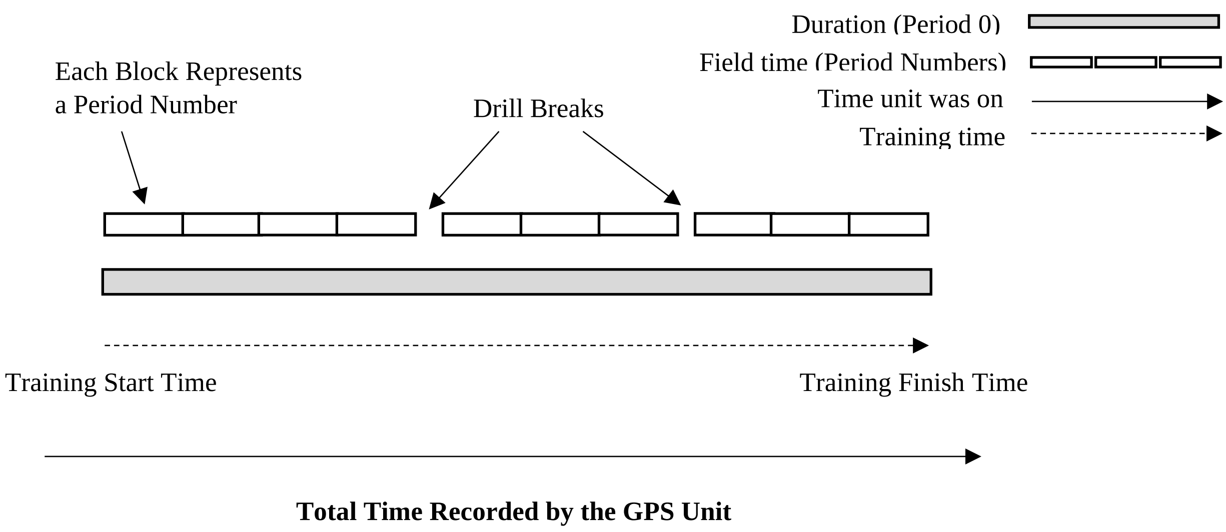


Figure 3.2: Visual representation of the timings reported by the GPS unit. The period zero field time values have been used in this study to track training and match volume.

3.2.5.2 Estimating Training Volume for Pitch-Based Sessions

If a player's duration data were missing for any pitch-based training session, then those data points were estimated. This was achieved by using the data from players who had also completed the training session, and were playing in the same position (e.g., if a Hooker had a blank time, then the time was taken as the average from other Hookers completing the same session). If no other players in the same position had completed the training session however, then the data was estimated by taking the average of Forwards/Backs as a whole. In certain scenarios players were found to exist within the period numbers of CTR files, but not in the period zeros (period numbers represent the individual drills performed by the player, whereas period zeros cover the whole training session, see Figure 3.2). In these circumstances, the last period number time (i.e., the time the player completed their final drill) was subtracted from the first drill time to give that players period zero time (total volume from the start of the first drill to the end of the last drill). This prevented data from being overlooked in the study. In rare instances where there was an RPE time for a training session but the duration and field time value form the CTR file were blank (e.g., unit ran out of charge), then the player's duration value was taken from the RPE database via the volume column (this occurred in the 2018/19 season only). If there was no duration or field time value, and the session was not in the team RPE database, then the data was discarded based on there being no accurate method to estimate the data. Over the course of the two seasons, 88.4% of the data (33,781 data points) was completed data, and 11.6% (4443 data points) needed to be estimated.

3.2.5.3 Quantifying Gym-Based Training Volume

The RPE databases for each team were the 'gold-standard' of gym-based training volume (hours spent training) data and were used in every instance possible (i.e., if there was an entry for the same session in the RPE database and the weights-log database, the training volume was taken from the RPE database). If there was no entry in the RPE database (i.e., the training volume for that session was not given), but the weights-log confirmed that gym-based training had been performed, then the weights-log data was used to estimate that player's gym-based training volume. Noteworthy is that the information used in the 2017/18 weights-log differed in relation to the information used for the 2018/19 weights-logs when estimating training volume. This was due to one team needing training volume estimations in the 2017/18 season and two teams needing training volume estimations in the 2018/19 season (the information provided by each team was different, and thus different formulas had to be used for each season).

3.2.5.4 Quantifying Gym-Based Training Volume for the 2017/18 Season

For training sessions that had a weights-log entry but not an RPE database volume entry, training volume had to be estimated. To achieve this, all weights-log training sessions that were also in the RPE database were synced, meaning all of those synced weights-log entries had a known gym-based training volume. The volume load (VL) value for those weights-log sessions with a known training volume were then taken. This was calculated by taking the load (weight) lifted for each exercise, and the number of sets and repetitions performed (see Table 3.7), and was calculated as:

$$VL = (Load \text{ x } reps) \text{ x } sets\ performed$$

$$e.g., (110 \text{ x } 4) \text{ x } 2$$

$$VL = 880$$

The VL data for each training exercise was then summed to give each player's total session VL. The summed VL data was then divided against the known training session duration (noted in the RPE database). For all sessions where there was a known session VL and session duration, the mean of VL divided by the session duration was then calculated, and used to estimate the duration of weight-log exercises (constant value = 0.02. For example, 880 divided by 0.02 = 17.6, see Table 3.8). This data was then summed in a pivot table to provide total session duration for each player across each gym-based training session (See Table 3.9). The known minimum and maximum values (20 minutes and 90 minutes, respectively) from the RPE database were then used as cut off points for the estimated data (i.e., if a session was less than the minimum or above the maximum, the minimum or maximum value was substituted in its place). Over the course of the 2017/18 season, 80.2% of the gym-based data was completed data (9,439 data points), 0.4% needed estimated from other players (44 data points) and 19.5% was estimated via the aforementioned formula (2291 data points).

Table 3.7: Example of the data provided in the Glasgow weights-log.

Player	Exercise	Weights Category	Load	Sets	Reps	VL
A	Squat	Lower Body Weights	110	2	4	880
A	Squat	Lower Body Weights	120	2	4	960
B	Leg press	Lower Body Weights	170	2	6	2040
C	Squat	Lower Body Weights	120	4	4	1920
C	Squat	Lower Body Weights	130	3	3	1170

Table 3.8: Example of the estimated duration values created from the VL values provided.

Player	Exercise	Weights Category	Load	Sets	Reps	VL	Duration
A	Squat	Lower Body Weights	110	2	4	880	17.6
A	Squat	Lower Body Weights	120	2	4	960	19.2
B	Leg press	Lower Body Weights	170	2	6	2040	40.8
C	Squat	Lower Body Weights	120	4	4	1920	38.4
C	Squat	Lower Body Weights	130	3	3	1170	23.4

Table 3.9: Example of the estimated session durations from data provided in Table 3.8.

Date	Player	Session Type	Estimated Session Duration
05/06/2017	A	Lower Body Weights	37
05/06/2017	B	Lower Body Weights	41
05/06/2017	C	Lower Body Weights	62

3.2.5.5 Quantifying Gym-Based Training Volume for the 2018/19 Season

In order to standardise how the gym-based volume data was estimated for the two teams across the 2018/19 season, a formula was created that could be applied to both teams weights-log database (the criteria given in both these databases slightly differed, however both provided the exercise, the load and the reps performed). The formula used two main metrics to create an estimated duration value. Firstly, a "VL" metric for each data entry was created from the load and rep values (load x reps) provided in the weights-log databases (see Table 3.10). Thereafter, a column highlighting the "Number of Lifts" performed was created using the number of rows each player had entered for that day (each row represents a set completed by that player for a given exercise) (see Table 3.11).

The base 10 logarithm of "Number of Lifts" x "Session VL" was then calculated from each row within the weights-log database. A pivot table was then used on the dataset to provide a sum of VL and maximum number of lifts for each session completed by each given player (see Table 3.11). The pivot table values - which were independently predictive of the aforementioned metrics - were then multiplied by a constant in order to provide a standardised duration estimation across all data points for both teams.

Similar to the 2017/18 weights-log training estimation, only sessions that were in the RPE database and the weights-log database were used to create the constant value. Again, this is because the exercises performed in the weights-log, along with the number of lifts, VL, load and reps could then be matched to a known training time (taken from the RPE database). The constant value was calculated by taking the session volume, divided by Log10 (Number of Lifts x Session VL) (via the weights-log database). The mean constant (mean constant = 17.45) for all training sessions with a known volume was then used to estimate the volume of gym-based training sessions in the weights-log. This was achieved by multiplying the Log10 value by the Constant (see Table 3.12). Over the course of the 2018/19 season, 63.5% of the gym-based data was completed data (4,911 data points), 0.8% needed estimated from other players (64 data points) and 35.8% was estimated via the aforementioned formula (2780 data points).

Table 3.10: Example of gym-based training data used to create training volume from team weight-logs.

Player	Exercise	Weights Category	Session Type	Number of Lifts	Load	Reps	Session VL
A	Squat	Lower Body Weights	Full Body Weights	2	100	5	500
A	Shoulder Press	Upper Body Weights	Full Body Weights	2	40	5	200
B	Paused DB Bench	Upper Body Weights	Upper Body Weights	1	128	8	1025
C	Ecc Bench Press	Upper Body Weights	Upper Body Weights	1	160	2	320

Table 3.11: Example of the data summed for VL and maximum number of lifts performed in that session using team weight-log data (as given in Table 3.10).

Date	Player	Session Type	Sum of VL	Max of Number of Lifts
04/06/2018	A	Full Body Weights	700	2
04/06/2018	B	Upper Body Weights	1025	1
04/06/2018	C	Upper Body Weights	320	1

Table 3.12: Example of how the duration values were estimated using data from Tables 3.10 and 3.11.

Date	Player	Session Type	VL	Number of Lifts	Log10	Constant	Duration
04/06/2018	A	Full Body Weights	700	2	3.15	17.45	54.9
04/06/2018	B	Upper Body Weights	1025	1	3.01	17.45	52.5
04/06/2018	C	Upper Body Weights	320	1	2.51	17.45	43.7

3.2.5.6 Quantifying Match Volume

Match volume was defined as: "*the total time a player was involved in match play, from either kick-off or from the moment the player was substituted onto the field, until the player was either substituted off the field, or the referee blew for full-time, excluding the half-time break*". Periods of time were excluded for any player who came off the pitch for a yellow card, head injury assessment or blood injury for the duration they were side-lined.

3.2.5.7 Estimating Match Volume

For data that was blank following match play, the video footage of that player was analysed to see when the player started/finished the match, and was thereafter manually entered. Within Glasgow's 'Team GPS Database', there were rare occasions when players would have multiple small match times (e.g., four entries of 8 minutes), instead of one full entry (e.g., 32 minutes).

Where this had occurred, that player’s start and end time were checked via video footage to evaluate the time the player was on the pitch for. If the number of small entries (when summed) equalled the video footage match time, then the multiple data entries were summed to give one total match time for that player (e.g., if there was four entries of 8 minutes, the total time would have been summed and taken as 32 minutes). Otherwise, if the player started and finished the match at the exact time as another player (checked via video footage) with accurate match data however, then this data was used to accurately sort match volume. If the player had a unique match volume, then the video footage match time was taken. Over the two seasons, 98.7% (3137 data points) of the data was completed, and 1.3% had to be estimated (40 data points).

3.2.5.8 Actual vs. Expected Players Training Each Week of the Season

Once the master database was complete and all training and match volume data was quantified, team weekly data was analysed in order to assess the utility of the data in terms of player training consistency. Team data for the 2017/18 season and 2018/19 data was separated into players vs. training weeks, and the number of training sessions complete each week by each player. In addition to this, all players who were not training on any given week were further analysed. If a player’s absence could be justified (e.g., a time loss injury had occurred or that player was away on international duty), then the player was not ‘expected to be training’. Any full-time player who was not training on any given week without plausible cause was included as ‘expected to be training’. There was no reported difference between actual and expected players training each week, therefore data comprehensiveness and completeness were considered valid (the actual vs. expected figures over the course of the 2017/18 and 2018/19 season are presented in Figures 3.3 and 3.4, respectively). The percentage of players expected to be training each week of the 2017/18 and 2018/19 season for Edinburgh Rugby and Glasgow Warriors are shown in Figure 3.5.

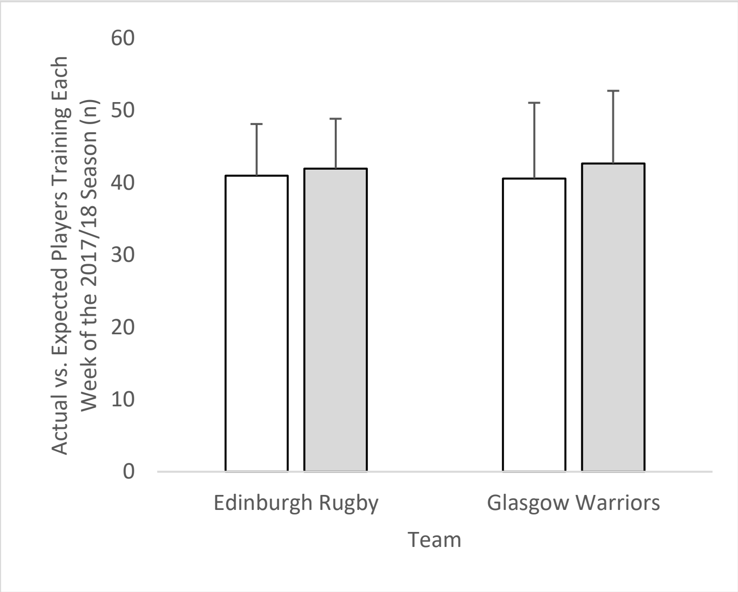


Figure 3.3: Number of actual vs. expected players training each week over the 2017/18 season for Edinburgh Rugby and Glasgow Warriors.

NOTE: Error bars show standard deviation; white bars, actual players training; grey bars, expected players training.

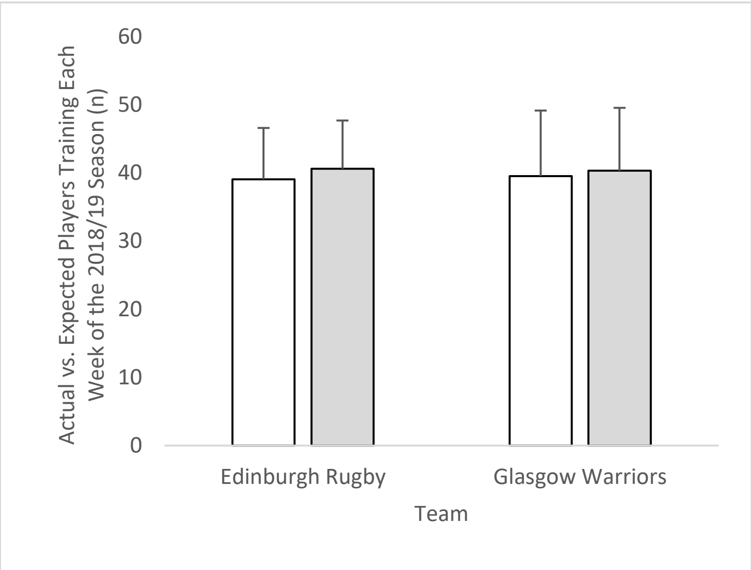


Figure 3.4: Number of actual vs. expected players training each week over the 2018/19 season for Edinburgh Rugby and Glasgow Warriors.

NOTE: Error bars show standard deviation; white bars, actual players training; grey bars, expected players training.

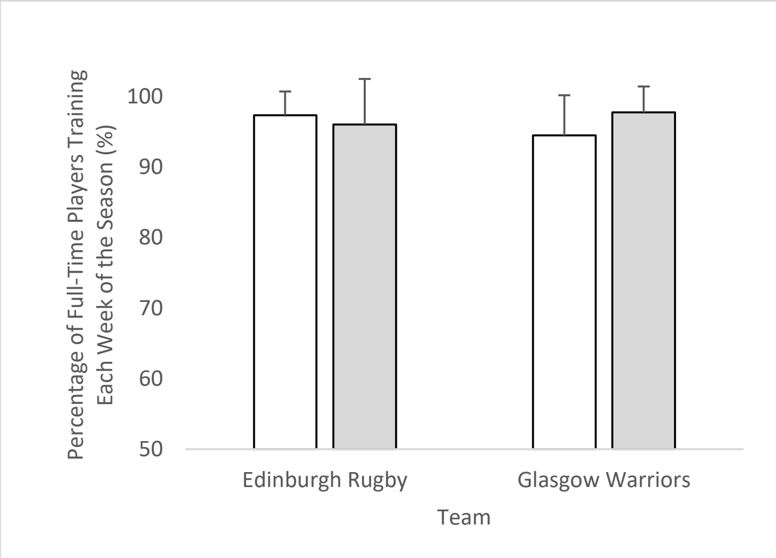


Figure 3.5: Percentage of players training each week over the 2017/18 and 2018/19 seasons for Edinburgh Rugby and Glasgow Warriors.

NOTE: Error bars show standard deviation; white bars, 2017/18 season; grey bars, 2018/19 season.

3.2.6 Recording of Injuries and Injury Definitions (All Subsequent Studies)

3.2.6.1 The Recording of Injury Data

Player injury data was collected from all players across the three SRU contracted squads used in this study throughout the 2017/18 and 2018/19 seasons. Medical data were collected and recorded on EDGE 10 (2017/18) and Microsoft Excel (2018/19) each week. This was completed by the qualified team medical personnel associated with each team. Injury diagnoses were recorded using the Orchard Sports Injury Classification System version 10 (Rae and Orchard, 2007).

3.2.6.2 Injury Definitions

Injuries were recorded according to the World Rugby Consensus Group, where an injury was defined as "*Any physical complaint, which was caused by a transfer of energy that exceeded the body's ability to maintain its structural and/or functional integrity, that was sustained by a player during a rugby match or rugby training*." (Fuller *et al.*, 2007b, p. 329). Injuries were recorded using a fully inclusive time loss definition ("*any injury that prevents a player from taking a full part in all training activities typically planned for that day and/or match play for more than 24 hours from midnight at the end of the day the injury was sustained*") (Brooks *et al.*, 2008, p. 864). As well as the medical attention definition ("*an injury that resulted in a* *player receiving medical attention*") (Fuller *et al.*, 2007b, p. 329). Recurrent injuries were defined as "*an injury of the same type and at the same site as an index injury and which occurs after a player's return to full participation from the index injury*" (Fuller *et al.*, 2007b, p. 329). Injury incidence was defined as injuries/1000 player match or training hours, whereas injury severity was defined as "*the number of days that had elapsed between the day the injury was sustained until the player returns to full training and availability for match-play selection*" (Fuller *et al.*, 2007b, p. 329). Severity was classified as minimal (2–3 days); mild (4–7 days); moderate (8–28 days) and severe (>28 days) (Fuller *et al*., 2012). Injuries were further broken down into 'contact' and 'non-contact'. Contact injuries were defined as any injury that resulted *"from contact with another player or object*" (Fuller *et al.*, 2007b, p. 329), whereas non-contact injuries were defined as any injury that occurred following no contact with another player or object. All injury definitions are in accordance with the methods described in the International Rugby Board (IRB) consensus statement on injury definitions (Fuller *et al.*, 2007b). The incidence, severity and causes of all injuries were then analysed and grouped into the associated playing position. This allowed the injury epidemiology data for all playing positions to be identified.

3.2.7 Data Analyses following the Quantification of all Training and Match Volume Data

3.2.7.1 Daily and Weekly Training Volume

Daily training volume was calculated by summing the total training time in a day (e.g., if a player participated in two training sessions on a given day at 60 minutes each, that player's daily training volume would be 120 minutes). Daily volume was then summed over each 7-day period to give that player's total weekly training volume. Weekly blocks were categorised from Monday to Sunday.

3.2.7.2. Week-to-Week Change in Training Volume

A player's week-to-week change was the absolute difference between the current week's total and the previous week's total. Week-to-week change was then calculated by taking the sum of the current week's volume and subtracting it from the sum of the previous week's volume (Cross *et al.*, 2016; Rogalski *et al.*, 2013; Williams *et al.*, 2017a).

3.2.7.3. Two, Three and Four-week Cumulative Training Volume

A player's 1-, 2-, 3- and 4-week cumulative volume was taken as the sum of total training volume for the previous 7, 14, 21 or 28 days, and was simply calculated by summing the accumulated rolling values over the specified time period (7, 14, 21 or 28 days) (Cross *et al.*, 2016; Rogalski *et al.*, 2013; Williams *et al.*, 2017a).

3.2.7.4. The Acute: Chronic Workload Ratio (Traditional Coupled Rolling Average)

The ACWR was taken as the ratio between a player's most recent 1-week volume (acute) and their previous 4-week rolling average (chronic). It was calculated by taking a player's acute volume and dividing it by their chronic volume (Hulin *et al.*, 2014; Hulin *et al.*, 2016b; Windt and Gabbett, 2016). This method included the acute data (current weekly volume) in the chronic calculation, and is thus coupled. The formula for this is below:

$$\frac{A}{0.25 * (A + W2 + W3 + W4)}$$

*'A' = the acute (current weekly) volume/load. The chronic load values are then calculated using A, W2 (preceding 2nd week), W3 (preceding 3rd week) and W4 (preceding 4th week).

The ratio between the most recent weekly volume (acute workload) and the average of the acute load plus the preceding 3 weeks (chronic workload) provided a coupled ACWR score.

3.2.7.5. The Acute: Chronic Workload Ratio (Uncoupled Rolling Average)

The ACWR was taken as the ratio between a player's most recent 1-week volume (acute) and the preceding 3-week rolling average (chronic). Unlike the coupled method, the uncoupled method did not include the acute workload in the chronic calculation, and was thus given as:

$$\frac{A}{0.3333 * (W2 + W3 + W4)}$$

*'A' = the acute (current weekly) volume/load. Chronic volume/load is then calculated using W2 (preceding 2nd week), W3 (preceding 3rd week) and W4 (preceding 4th week).

The ratio between the most recent weekly volume (acute) and the average of the preceding 3 weeks (chronic) provided an uncoupled ACWR score.

3.2.7.6. The Acute: Chronic Workload Ratio (Exponentially Weighted Moving Average)

To begin the EWMA ACWR calculation, the first value in the series was recorded as the average of the first 7-days volume. Thereafter the EWMA for a given day was calculated by:

$$EWMA_{today} = Volume_{today} \times \lambda a + ((1 - \lambda a) \times EWMA_{yesterday})$$

Where λa is equal to the degree of decay and given by:

$$\lambda a = 2/(N + 1)$$

N is the chosen time of decay (Williams *et al.*, 2016; Menaspà, 2017; Murray *et al.*, 2017b). The chosen time of decay in this study was 7 days for acute workload and 28 days for chronic. The value on day 28 was the ACWR for that given period. Finally, the EWMA acute workload was divided by the EWMA chronic workload (Williams *et al.*, 2016; Murray *et al.*, 2017b). Injury risk was analysed by assessing if an injury occurred in the subsequent day/week, in relation to the ACWR ratio. For subsequent-daily analysis, the injury indicator was moved up one day so that the ACWR value that the athlete started the session with, on the day of their injury, is the one that gets linked to the injury (i.e., it doesn't include the load from the day of the injury). For longer time lags, the maximum EWMA ACWR value from the preceding 7-days was taken. This prevented the sample size from being artificially inflated, as would have been the consequence of taking all seven days of 'injury indicators' prior to the day of the injury. The maximum value was chosen, as the mean value may have over-looked very high ACWR values (e.g., spikes in training volume).

3.2.7.7. Match Exposure

Chronic match exposure (match exposure over a 12-month period) was calculated as the total number of matches a player was involved in >20 minutes for the 2017/18 and 2018/19 seasons. The inclusion of match involvements of >20 min were used based on previous research assessing the influence of match exposure on injury risk (Williams e*t al.*, 2017b). Match involvements < 20 min have previously been deemed too minor to have a consequential impact on injury, and were thus excluded from the present study (Williams e*t al.*, 2017b). The accumulated match exposure over each 12-month season was based off the number of match involvements because injury risk may also be influenced by the preparation for such involvements, such as training and travelling to and from match venues (Williams e*t al.*, 2017b). Acute match exposure was calculated as a player's full-game equivalent [FGE], which is a player's total match volume divided by 80 in the preceding 30 days (1-month match exposure). For the analysis of FGE's and monthly match exposure analysis, only match exposures >20 minutes were included. These timeframes have previously been used by Williams e*t al.* (2017b), based on team sport fixture congestion and seasonal structures.

3.2.7.8. Injury Incidence, Severity and Burden

Injury incidence was calculated as the number of training and match injuries per 1000 hours of training and match volume (Brooks *et al.*, 2005; Brooks *et al.*, 2005b; West *et al.*, 2019). Mean severity was calculated as the total number of training and match injuries divided by the total number of days absent. Median severity was also calculated to show the influence that a small number of high severity injuries can impose on mean severity (West *et al.*, 2019). This was calculated by taking the mid-point in the range of severities associated with training and match injuries. Injury incidence and mean severity values were used to calculate injury burden (days lost per 1000 hours) (Brooks *et al.*, 2005). Injury incidence, severity and burden were calculated for total training and match volume, as well as mean values. In addition, differences for training type (on-pitch vs. gym-based), training month, seasonal phase (pre-season vs. in-season), and positional groups were assessed. Weekly training volume as a factor for training and match injury was analysed by splitting the data into equal frequency quintiles (< 5.81 hours; 5.82- 6.49 hours; 6.50 - 6.85 hours; 6.86 - 7.22 hours; > 7.22 hours) (Brooks *et al.*, 2008). In addition, due to differences in match preparation times for weeks with earlier match days (Friday matches), versus weeks with later match days (Saturday matches), the influence of weekly training volume for Friday matches (< 4.96; 4.96 - 5.55; 5.56 - 5.89; 5.9 - 6.42; > 6.42) and Saturday matches (< 5.74; 5.74 - 6.17; 6.18 - 6.51; 6.52 - 6.9; > 6.9) were also assessed. The incidence, burden and mean number of injuries per player (calculated as total injuries divided by total number of players) for training and match volume categories were assessed. The influence of accumulated match exposure on injury risk was assessed using the 12-month and 30-day match exposure variables outlined in the data analysis (William *et al.*, 2017). These variables were assessed in relation to injury incidence and burden, as well as the mean number of player injuries.

3.2.8. Statistical Analysis

As per section 3.2.7 in the Data Analysis, daily training volume were summed to provide weekly blocks. This data was then averaged over the two-seasons for each player to give weekly training volume per player. Match exposure data was calculated separately for each season so that the influence of match exposure over 12-month and 30-day periods were not influenced based on averages (i.e., it was just the match exposure for that month/year independently). For each load-monitoring variable (cumulative volumes, weekly change, and ACWR metrics) data was split into quintiles (very low, low, medium, high and very high) based on a weekly basis (i.e., were not averaged). The lowest range group (very low) was used as a reference group. Volume values and injury data (injury vs. no injury) were modelled using binary logistic regression. The load-monitoring variables were independently modelled as the predictor variables, and injury/no injury as the dependent variable. Odds Ratio was used to determine the magnitude of the injury risk. When the OR was greater than 1, an increased odds of injury was reported. Conversely, when an OR was less than 1, a decreased odds of injury was reported. For an OR to be significant, 95% confidence intervals (CI) would not contain the null of 1.00. Confidence intervals were calculated for a one sample, dichotomous outcome via proportions (Kirkwood and Sterne, 2010). Data were analysed using IBM SPSS Statistics V.26.0 (IBM Corporation, New York, USA). Data is reported as means ± standard deviation (SD) unless specified as 95% confidence intervals. Significance was accepted at $p<0.05$.

3.3 RESULTS

3.3.1 Total Training Volume

Over the course of the study period, players spent a total of 58,044.3 hours training (On-pitch training: 41,663.5 player-hours; Gym-based training: 16,380.7 player-hours). For Forwards and Backs, this equated to 32,352.8 hours (On-pitch training: 23,360.8 player-hours; Gym-based training: 8,992 player-hours), and 25,691.5 hours (On-pitch training: 18,302.8 player-hours; Gym-based training: 7,388.7 player-hours), respectively.

3.3.2 Mean Weekly Player Training Volumes

Throughout the study, players averaged 6.7 (± 3.2) hours of training per week (On-pitch training: 4.8 [± 2.6] player-hours; Gym-based training: 1.9 [± 1.8] player-hours). Forwards completed 6.7 (± 3.2) hours of training per week (On-pitch training: 4.8 [± 2.6] player-hours; Gym-based training: 1.9 [± 1.8] player-hours), and Backs completed 6.6 (± 3.1) (On-pitch training: 4.7 [± 2.6] player-hours; Gym-based training: 1.9 [± 1.8] player-hours) hours of training per week.

3.3.3 Total Match Exposure

Players spent a total of 3264.5 hours in match play (pre-season friendlies = 178 hours; PRO 14 = 2,074 hours; European matches [challenge cup and champions cup] = 648 hours; International matches [autumn tests, six nations, summer tour] = 364.4 hours) (see Supplementary Figure 5 for visual representation). Supplementary Figure 6 also provides a breakdown of match exposure over each month of the season for each match type.

3.3.4 Training and Match Injury Data

A total of 305 training injuries (Forwards = 171, Backs = 134) were sustained over the study period. Of these 305 training injuries, 258 occurred during on-pitch training (Forwards = 141, Backs = 117), and 24 occurred during gym-based training (Forwards = 15, Backs = 9). A total of 23 training injuries were noted with unknown mechanisms and were thus not categorised into on-pitch or gym-based, but were included in the analysis for all training injuries. A total of 429 match injuries were sustained over the two seasons (Forwards = 223, Backs = 206).

3.3.5 Training Injury Incidence

The incidence of training injuries was 5.3 (95% CIs: 4.7–5.8) injuries per 1000 player-training hours (Forwards = 5.3 [95% CIs: 4.5–6.1]; Backs = 5.2 [95% CIs: 4.3–6.1]). On-pitch training vs gym-based training incidence rates were 6.2 (95% CIs: 5.4–6.9) injuries per 1000 player-training hours (Forwards = 6.0 [95% CIs: 5.0–7.0]; Backs = 6.4 [95% CIs: 5.2–7.5]), and 1.5 (95% CIs: 0.9–2.1) injuries per 1000 player-training hours (Forwards = 1.7 [95% CIs: 0.8–2.5]; Backs = 1.2 [95% CIs: 0.4–2.0]), respectively.

3.3.6 Match Injury Incidence

Match incidence was highest for pre-season friendly matches at 140.3 (95% CIs: 89.3–191.3) injuries per 1000 hours of match play. International matches had the second highest incidence rate at 137.2 (95% CIs: 101.9–172.5) injuries per 1000 match hours. PRO 14 matches had an incidence rate of 132.6 (95% CIs: 118–147.2) injuries per 1000 hours of match play. European matches had the lowest incidence rate at 121.9 (95% CIs: 96.7–147.1) injuries per 1000 hours of match play (see Supplementary Figure 11 for visual representation).

3.3.7 Training Severity

A total of 6401 days were lost from training injuries (pre-season injuries = 2296 days lost; in-season injuries = 4105 days lost). The mean injury severity was 21 days per training injury (Forwards = 16.1; Backs = 24.8 days). The severity of on-pitch training injuries was 20.6 days (Forwards = 24.3; Backs = 16.2), and gym-based was 16.2 days per injury (Forwards = 21.2; Backs = 7.9). Mean training severity for pre-season injures was 25.8 days (Forwards = 32.4; Backs = 17.3). Mean in-season severity per injury was 19 days (forwards = 21.7; backs = 15.6).

The median severity for training injuries was 7 days. Total and average training severity for positional groups are presented in Table 1.

3.3.8 Match Severity

A total of 9212 days were lost from match injuries (pre-season = 431 days lost; in-season = 8781 days lost). The mean severity for match injuries was 21.5 days per injury (Forwards = 21.8; Backs = 21.1). For pre-season and in-season phases, mean match severity was 17.2 days (Forwards = 12.6; Backs = 20.9) and 21.7 (Forwards = 22.3; Backs = 21.2) days, respectively. The median injury severity for match play was 7 days. Total and average match severity for positional groups are presented in Table 3.13

Table 3.13: Training and match total and mean severities for positional groups over the 2017/18 and 2018/19 seasons.

Position	Training Severity (days absence)	Mean Training Severity (95% CIs)	Match Severity (days absence)	Mean Match Severity (95% CIs)
Prop	1120	20.4 (10.4 - 30.2)	898	16.9 (9.2 - 24.6)
Hooker	561	25.5 (12.1 - 38.8)	1021	23.7 (14.7 - 32.8)
Second Row	1311	32 (13.2 - 50.7)	808	20.2 (10.6 - 29.8)
Back Row	1254	23.7 (10.5 - 36.81)	2131	24.5 (15.3 - 33.7)
Stand Off	263	11.4 (4.9 - 18)	420	13.6 (5.8 - 21.3)
Scrum Half	174	13.4 (6.8 - 20)	506	23 (14.0 - 32.0)
Centre	315	8.1 (5.4 - 10.8)	1708	21.6 (13.1 - 30.1)
Back 3	1403	23.8 (10.6 - 36.9)	1720	23.2 (14.9 - 31.6)

3.3.9 Training and Match Injury Burden

The burden of training injuries was 120.2 days absence per 1000 training hours (Forwards = 143.5 days absence per 1000 hours; Backs = 90.9 days absence per 1000 hours). The burden of pre-season training injuries was 158.4 days absence per 1000 hours, and the burden of in-season injuries was 94.3. The burden of match injuries was 2825.4 days absence per 1000 match hours (Forwards = 2769.4 days absence per 1000 hours; Backs = 2882.8 days absence per 1000 hours). Pre-season match injury burden was 2419 days absence per 1000 match hours, whereas in-season match injury burden was 2845.1 days absence per 1000 match hours.

3.3.10 The Influence of Training Volume on Training Injuries

There was a negative linear relationship between mean weekly training volume and training injury incidence. Training injury incidence was at its highest (7.6 [95% CIs: 5.4 – 9.7] injuries per 1000 hours) in the lowest training volume group (< 5.81 hours per week), and at its lowest (3.6 [95% CIs: 2.6 – 4.6] injuries per 1000 hours) for players in the highest mean training volume per week (> 7.2 hours per week). Training incidence was higher for players with 'intermediate' weekly training volumes (6.5 – 6.85 hours per week), compared to 'low intermediate' (5.82 – 6.49 hours per week), 'high intermediate' (6.86 – 7.22 hours per week) and high (> 7.22 hours per week) training volumes per week (see Figure 3.21). Injury burden followed the same pattern; players in the lowest weekly training volume category (< 5.81 hours per week), had the highest burden values (379.9 [95% CIs: 286.3 – 504.1] days absent per 1000 hours), and players in the highest mean weekly training volume category (> 7.2 hours per week), had the lowest burden values (33.7 [95% CIs: 25.5 – 44.4] days absent per 1000 hours).

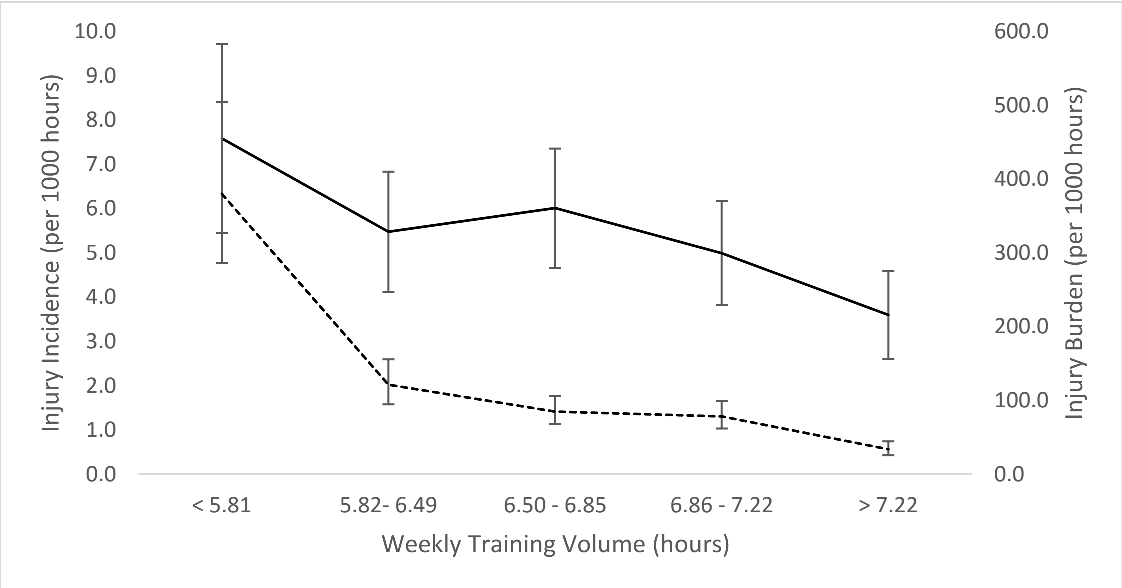


Figure 3.6: The incidence and burden of training injuries as a function of mean weekly training volume per player over the 2017/18 and 2018/19 seasons.

NOTE: Solid line, training incidence; dashed line, training burden; error bars, 95% confidence intervals.

3.3.11 The Influence of Training Volume on Match Injuries

As with training injury incidence, match injury incidence was at its highest (175.6 [95% CIs: 136.2 – 215] injuries per 1000 hours) in the lowest training volume group (< 5.81 hours per week). Match injury incidence was lowest (120.8 [95% CIs: 98.1 – 143.6]) injuries per 1000 hours) for players with a 'high intermediate' mean weekly training volume of 6.86 – 7.22 hours per week. Similar to training incidence, match incidence was higher for players with 'intermediate' weekly training volumes (6.5 – 6.85 hours per week), compared to 'low intermediate' (5.82 – 6.49 hours per week), 'high intermediate' (6.86 – 7.22 hours per week) and high (> 7.22 hours per week) training volumes per week (see Figure 3.22). Match injury burden was highest (4666.2 [95% CIs: 3645.2 – 5973.1] days absent per 1000 hours) for players in the lowest weekly training volume category (< 5.81 hours per week), and lowest (1974.2 [95% CIs: 1587.9 – 2454.6] days absent per 1000 hours) for players with a high mean weekly training volume (> 7.22 hours per week).

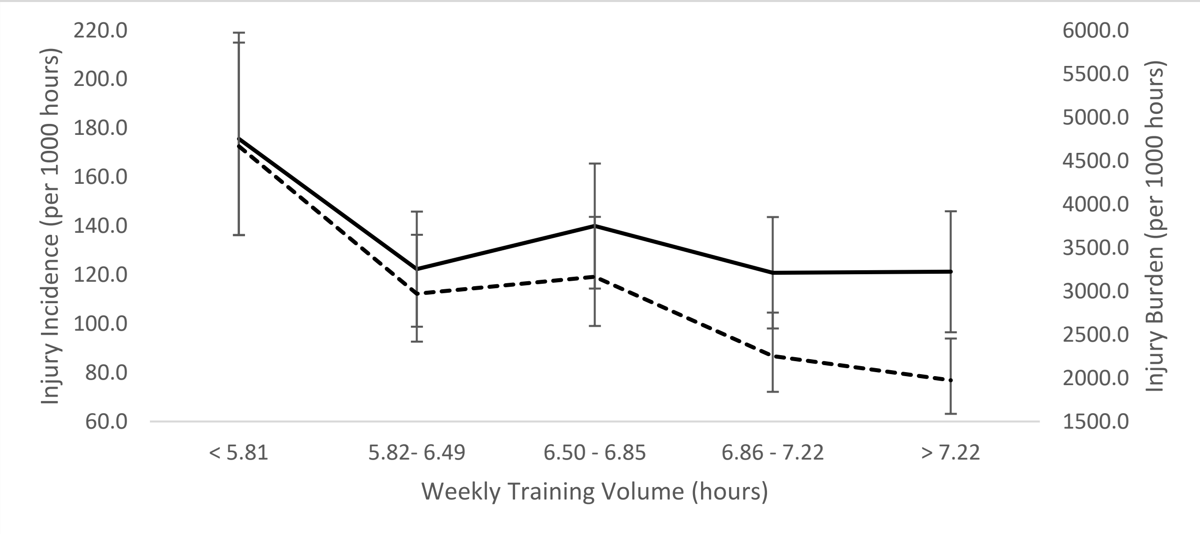


Figure 3.7: The incidence and burden of match injuries as a function of mean weekly training volume per player over the 2017/18 and 2018/19 seasons.

NOTE: Solid line, match incidence; dashed line, match burden; error bars, 95% confidence intervals.

3.3.12 The Influence of Match Exposure on Injury Risk

Players' 12-month match exposure was assessed in relation to match injury incidence and burden. Incidence was highest in players with < 5 games of exposure (202.2 [95% CIs: 113.7 – 290.7] injuries per 1000 hours) (See Figure 3.26). Incidence reduced for players between 5-

9 match exposures (161.2 [95% CIs: 113.7 – 208.8] injuries per 1000 hours), but there was an increase for players who were exposed to 10-14 matches over 12-months (173.6 [95% CIs: 138.6 – 208.6] injuries per 1000 hours). Incidence thereafter dropped for players exposed to 15-19 matches (134.3 [95% CIs: 109.7 – 158.9] injuries per 1000 hours), and continued to decline. Players exposed to > 25 matches had the lowest incidence rate of 109 (95% CIs: 87.5 – 130.5) injuries per 1000 hours. Burden was highest for players exposed to 5-9 matches a year (5072 [95% CIs: 3675.2 – 7001] days lost per 1000 hours). There was a gradual decrease in burden for player's exposed to 10-14, and 15-19 matches, however burden was drastically reduced for players exposed to 20-24 matches a year (1947 [95% CIs: 1616.5 – 2345.1] days lost per 1000 hours), and further declined for players exposed to > 25 matches (1269.5 [95% CIs: 1030.2 – 1564.6]). Noteworthy is that when the mean number of injuries per player were assessed, there was a linear relationship between match exposure and the number of injuries sustained to those players (see Supplementary Figure 18).

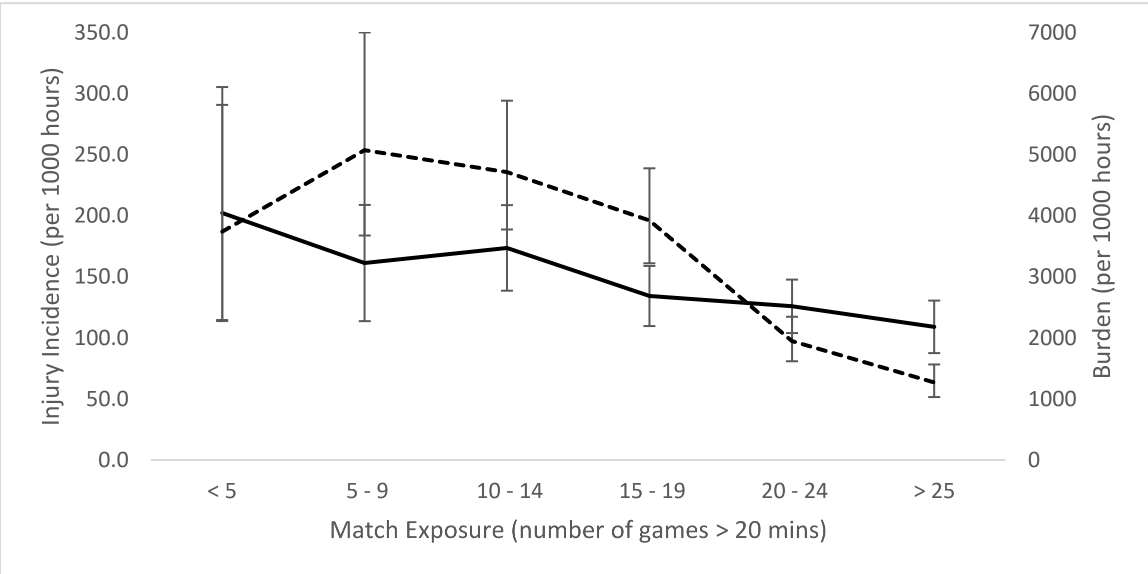


Figure 3.8: 12-month match exposure on injury incidence and burden.

NOTE: Solid line, injury incidence; dashed line, injury burden; error bars, 95% confidence intervals.

As well as 12-month match exposure, players' 30-day full equivalents were assessed in relation to match injury incidence, burden and the number of sustained injuries. Incidence declined as a player's 30-day FGE increased (See Figure 3.28). There was a large decline in incidence rate for player's exposed to 1 – 1.49 FGEs in a 30-day period (165 [130.2 – 199.9] injuries per 1000 hours), compared to lower FGE values (< 1 FGE = incidence rates > 300 injuries per 1000 hours). There was also a large decline for players exposed to 2 – 2.49 matches in a 30-day period compared to 1 – 1.49 FGEs (102 [95% CIs: 77.7 – 127.8] injuries per 1000 hours), with a very gradual decline in incidence thereafter. Burden also declined in a linear fashion as 30-day FGEs increased. Burden dropped substantially for players who were exposed to 1 – 1.49 FGEs in a 30-day period (5070 [95% CIs: 4025 - 6388] days lost per 1000 hours), compared to lower FGE values (< 1 FGE = > 8000 days lost per 1000 hours), and further declined for players exposed to 1.5 – 1.99 FGEs (2400 [95% CIs: 1851 - 3111] days lost per 1000 hours). Burden was lowest for players involved in > 3.5 FGEs in a 30-day period (847 [95% CIs: 665 - 1078] days lost per 1000 hours). The mean number of injuries sustained per player increased linearly with 30-day FGEs (see Supplementary Figure 19).

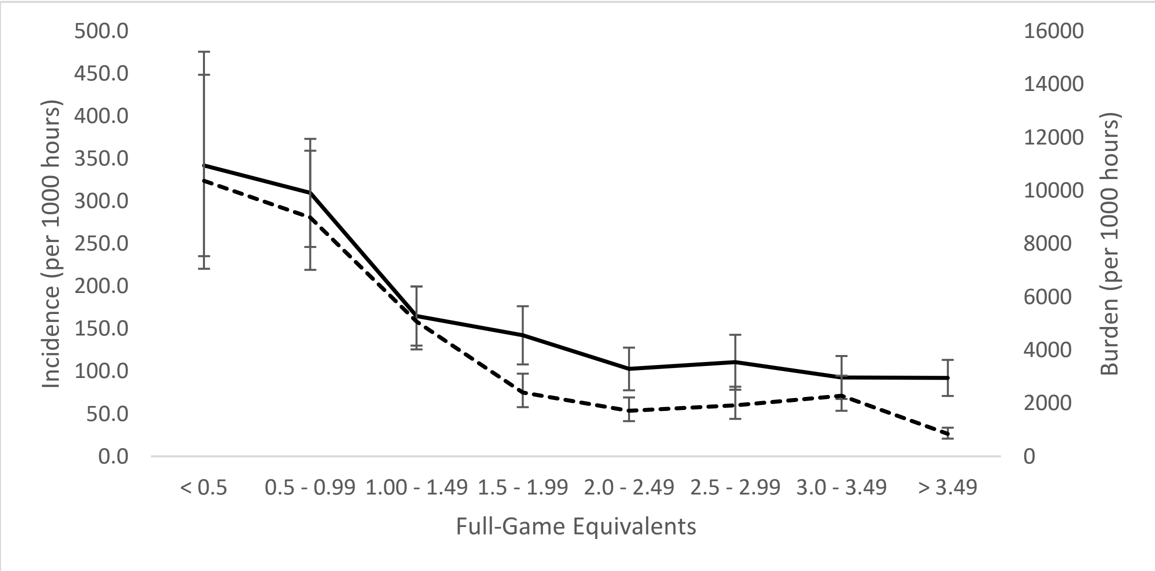


Figure 3.9: 1-month match exposure on injury incidence and burden with 95% confidence intervals.

NOTE: Solid line, injury incidence; dashed line, injury burden; error bars, 95% confidence intervals.

3.3.13 Training Volume on Injury Risk: The Cumulative Impact and Workload Ratios

1-, 2-, 3- and 4-Week Cumulative Training Volume and Weekly Change

An 'Intermediate Low' weekly training volume (5.5 – 6.8 hours) elicited the greatest overall subsequent week injury risk (Odds Ratio [OR] = 1.36, 95% CIs: 1.04 – 1.78, $p < 0.05$), closely followed a very high weekly training volume (> 9.6 hours; OR = 1.31, 95% CIs: 1.0 – 1.7, $p < 0.05$), compared to the reference category (See Table 3.14). For 2-week cumulative volume, players with 'Intermediate Low' and 'Intermediate High' 2-week volumes (11.11 - 13.13, and 13.14 – 15.04 hours, respectively) were at a significantly higher risk of being injured (OR =

1.39, 95% CIs: 1.05 – 1.82, $p < 0.02$; OR = 1.43, 95% CIs = 1.10 – 1.88, $p < 0.01$), compared to the reference category. Players with very high 2-week volumes were trending towards significantly higher injury risk (1.31, 95% CIs: 0.99 – 1.72, $p = 0.052$). For both 3- and 4-week cumulative volumes, 'Intermediate High' cumulative training volumes (19.42 – 22.21 hours and 25.57 – 28.98 hours, respectively) were associated with the highest injury risk (OR = 1.66, 95% CIs: 1.02 – 2.71, $p < 0.05$; OR = 1.71, 95% CIs = 1.31 – 2.22, $p < 0.01$), compared to the reference category. 'Intermediate Low' cumulative training volumes for 3- and 4-week cumulative volumes (16.18 – 19.41 hours and 21.51 – 25.56 hours, respectively) trended towards a significantly higher injury risk (OR = 1.58, 95% CIs: 0.97 – 2.6, $p = 0.07$; OR = 1.3, 95% CIs = 0.98 – 1.72, $p = 0.06$), compared to the reference category. Weekly change was not associated with an increased injury risk for any given category in comparison to the reference category ($p > 0.05$, see Table 3.14).

Weekly Coupled and Uncoupled Rolling Averages vs. Subsequent Week Injury Risk

There was no significant relationship reported between weekly rolling ACWR coupled values and player injury risk. Players in the 'High' and 'Very High' ACWR categories had the greatest ORs of 1.09 (95% CIs: 0.82 – 1.49, $p > 0.05$) and 1.06 (95% CIs: 0.77 – 1.46, $p > 0.05$). Players with an 'Intermediate Low' rolling coupled ACWR (OR = 0.94, 95% CIs: 0.69 – 1.26, $p > 0.05$) and 'Intermediate High' ACWR (OR = 0.86, 95% CIs: 0.64 – 1.15, $p > 0.05$), had the lowest OR values compared to the reference category (see Table 3.14). Similar findings are reported for the uncoupled weekly rolling ACWRs. Players in the 'High' and 'Very High' ACWR categories had the greatest injury risk (OR = 1.09, 95% CIs: 0.81 – 1.47, $p > 0.05$; OR = 1.15, 95% CIs: 0.88 – 1.51, $p > 0.05$). Players in the 'Intermediate High' category had the lowest injury risk (OR = 0.89, 95% CIs: 0.67 – 1.18, $p > 0.05$) however these findings were not significantly different from the reference category.

Daily Rolling and EWMA ACWR vs. Subsequent Week Injury Risk

There was a linear relationship for rolling daily ACWR categories and injury risk. Players with the greatest risk compared to the reference category were those in the 'Very High' ACWR category, reporting an OR of 5.44 (95% CIs: 3.33 – 8.9, $p < 0.001$). Nevertheless, even players in the 'Low' category reported a significantly higher injury risk compared to those in the reference category (OR = 1.88, 95% CIs: 1.09 – 3.24, $p < 0.05$) (see Table 3.14). For the

EWMA ACWR calculations in relation to subsequent week injury, there was a quadratic trend. Compared to the reference category, players in the 'Low' category had an OR of 0.51 (95% CIs: 0.21 – 1.21, $p > 0.05$), and those in the 'Intermediate Low' category had the lowest risk of injury, with an OR of 0.46 (0.21 – 1.03), which trended towards a significantly lower risk ($p = 0.058$). Player risk increased significantly compared to the reference category for player with 'Intermediate High' volumes (OR = 4.85, 95% CIs: 2.48 – 9.47, $p < 0.001$), and reported drastic increases in injury risk for those in the 'High' and 'Very High' categories (OR = 13.36, 95% CIs: 6.88 – 25.94, $p < 0.001$; OR = 15.70, 95% CIs: 8.03 – 30.68, $p < 0.001$) (see Table 3.14).

Daily Rolling and EWMA ACWR vs. Subsequent Day Injury Risk

Similar to subsequent week injury analysis, players with 'Low' to 'Very High' rolling ACWR values the day prior to an injury, had a significantly higher risk of sustaining an injury. Players with the lowest risk were those in the 'Intermediate Low' category (OR = 1.83, 95% CIs: 1.26 – 2.67, $p > 0.01$), however this was still significantly higher than those in the reference category. Players in the 'High' category had the greatest risk (OR = 2.27, 95% CIs: 1.54 – 3.33, $p < 0.001$), see Table 3.14. Players who had a 'Low' EWMA ACWR the day prior to injury had the lowest injury risk compared to the reference category (OR = 0.87, 95% CIs: 0.50 – 1.49), but this was not significant ($p > 0.05$). All other categories reported significant increases in injury risk compared to the reference category ($p < 0.05$). Players with the greatest risk were those with an 'Intermediate Low' EWMA ACWR the day prior to an injury (OR = 3.77, 95% CIs: 2.37 – 6.00, $p < 0.001$).

Table 3.14: Training volume risk factors for injury in professional Rugby Union.

	Very Low (Reference)	*Low*			*Intermediate Low*			*Intermediate High*			*High*			*Very High*		
Load Calculation	**Mean (Range)**	**Mean (Range)**	**OR (95% CIs)**	***P***	**Mean (Range)**	**OR (95% CIs)**	***P***	**Mean (Range)**	**OR (95% CIs)**	***P***	**Mean (Range)**	**OR (95% CIs)**	***P***	**Mean (Range)**	**OR (95% CIs)**	***P***
1-week Cumulative	1.82 (< 3.24)	4.48 (3.25 - 5.48)	0.99 (0.76 - 1.32)	0.95	6.19 (5.49 - 6.79)	1.36 (1.04 - 1.78)	**0.02** *	7.37 (6.8 - 7.99)	1.30 (0.99 - 1.67)	0.06	8.74 (8.00 - 9.60)	1.19 (0.90 - 1.56)	0.28	11.50 (> 9.61)	1.31 (1.00 - 1. 71)	**0.05** *
2-week Cumulative	4.62 (< 7.67)	9.49 (7.68 – 10.99)	1.09 (0.82 – 1.44)	0.57	12.13 (11 – 13.13)	1.39 (1.06 – 1.82)	**0.02** *	14.06 (13.14 – 15.04)	1.43 (1.1 – 1.88)	**0.01** *	16.22 (15.05 – 17.65)	1.25 (0.96 – 1.64)	0.12	21.31 (> 17.66)	1.31 (1.00 – 1.72)	**0.05** *
3-week Cumulative	7.22 (< 11.81)	14.17 (11.82 - 16.17)	1.22 (0.92 - 1.62)	0.16	17.86 (16.18 - 19.41)	1.42 (1.08 - 1.86)	**0.01** *	20.79 (19.42 - 22.21)	1.41 (1.08 - 1.86)	**0.01** *	23.81 (22.22 - 25.72)	1.27 (0.96 - 1.67)	0.10	30.40 (> 25.73)	1.30 (0.99 - 1.72)	0.06
4-week Cumulative	9.52 (< 16.06)	18.91 (16.07 - 21.5)	1.15 (0.87 - 1.53)	0.32	23.55 (21.51 - 25.56)	1.30 (0.99 - 1.72)	0.06	27.26 (25.57 - 28.98)	1.71 (1.31 - 2.22)	**0.00** *	31.06 (28.99 - 33.53)	1.19 (0.90 - 1.57)	0.23	39.22 (> 33.54)	1.2 (0.91 - 1.59)	0.20
Weekly Change (±)	0.32 (< 0.67)	1.04 (0.68 - 1.39)	0.8 (0.60 - 1.05)	0.10	1.80 (1.4 - 2.21)	1.13 (0.88 - 1.47)	0.34	2.77 (2.22 - 3.29)	1.08 (0.83 - 1.41)	0.55	4.03 (3.3 - 4.95)	1.06 (0.82 - 1.38)	0.65	7.38 (> 4.96)	1.09 (0.84 - 1.42)	0.51
Weekly Coupled Rolling ACWR	0.29 (< 0.5)	0.65 (0.5 - 0.75)	1.03 (0.73 - 1.44)	0.87	0.89 (0.75 - 1)	0.94 (0.70 - 1.26)	0.67	1.11 (1 - 1.25)	0.86 (0.64 - 1.15)	0.31	1.36 (1.25 - 1.5)	1.09 (0.80 - 1.49)	0.57	2.07 (> 1.5)	1.06 (0.77 - 1.46)	0.71
Weekly Uncoupled Rolling ACWR	0.25 (< 0.5)	0.64 (0.5 - 0.75)	0.87 (0.76 - 1.4)	0.85	0.88 (0.75 - 1)	1.02 (0.78 - 1.35)	0.88	1.11 (1 - 1.25)	0.89 (0.67 - 1.18)	0.41	1.37 (1.25 - 1.5)	1.09 (0.81 - 1.47)	0.57	2.77 (> 1.5)	1.15 (0.88 - 1.51)	0.30
Daily Coupled Rolling ACWR (SWI)	0.29 (< 0.5)	0.64 (0.5 - 0.75)	1.88 (1.09 - 3.24)	**0.02** *	0.88 (0.75 - 1)	3.07 (1.88 - 5.00)	**0.00** *	1.11 (1 - 1.25)	3.85 (2.38 - 6.23)	**0.00** *	1.36 (1.25 - 1.5)	5.11 (3.13 - 8.33)	**0.00** *	2.09 (> 1.5)	5.44 (3.33 - 8.90)	**0.00** *
Daily Coupled Rolling ACWR (SDI)	0.29 (< 0.5)	0.64 (0.5 - 0.75)	2.01 (1..35 - 3.00)	**0.00** *	0.88 (0.75 - 1)	1.83 (1.26 - 2.67)	**0.00** *	1.11 (1 - 1.25)	2.08 (1.44 - 3.01)	**0.00** *	1.36 (1.25 - 1.5)	2.27 (1.54 - 3.23)	**0.00** *	2.09 (> 1.5)	2.01 (1.35 - 2.98)	**0.00** *
Daily EWMA ACWR (SWI)	0.37 (< 0.5)	0.64 (0.5 - 0.75)	0.51 (0.21 - 1.21)	0.13	0.88 (0.75 - 1)	0.46 (0.21 - 1.03)	0.06	1.12 (1 - 1.25)	4.85 (2.48 - 9.47)	**0.00** *	1.35 (1.25 - 1.5)	13.36 (6.88 - 25.94)	**0.00** *	1.79 (> 1.5)	15.70 (8.03 - 30.68)	**0.00** *
Daily EWMA ACWR (SDI)	0.37 (< 0.5)	0.64 (0.5 - 0.75)	0. 87 (0.50 - 1.49)	0.60	0.88 (0.75 - 1)	1.89 (1.17 - 3.05)	**0.01** *	1.12 (1 - 1.25)	3.77 (2.37 - 6.00)	**0.00** *	1.35 (1.25 - 1.5)	2.98 (1.85 - 4.81)	**0.00** *	1.79 (> 1.5)	1.92 (1.13 - 3.26)	**0.02** *

NOTE: ACWR, acute: chronic workload ratio; EWMA, exponentially weighted moving average; SWI, subsequent week injury; SDI, subsequent day injury; OR, odds ratio; CI, confidence interval; *, signifies a significant difference from the reference group.

3.4 DISCUSSION

3.4.1 Main Findings

This study aimed to monitor indices of player training and match volume in elite Scottish Rugby Union players over the 2017/18 and 2018/19 seasons, and present an in-depth analysis of how training and match patterns can influence injury risk. In line with the current hypotheses, players with higher mean weekly training volumes had reduced training and match injury incidence and burden rates in this study. The researcher hypothesised a U-shaped relationship for match exposure, such that intermediate-high (15 – 30) match exposures would have a lower injury risk than those with low (< 15) and very high (> 30) match exposures over a season. Indeed, players with low 12-month match exposure had higher injury incidence and burden rates than players with greater exposure. Albeit, the match involvements in this study were not high enough to show any potential risks associated with extreme match exposure. Injury risk increased linearly as the ACWR increased > 1.00 for daily calculations. There was no association between injury risk and weekly ACWR measures (coupled vs. uncoupled), which likely reflects the lack of sensitivity with these calculations. Players with high 1-weekly cumulative volumes were at significantly greater injury risk compared to players with lower 1-weekly volumes. Greater training volumes (high and very high) appeared to be more protective of injury risk than lower training volumes (intermediate-low and intermediate-high) when cumulative volumes were over an extended period of time (i.e., 4-weekly).

3.4.2 Weekly Training Volume on Training and Match Injuries

Training and match incidence and burden rates in the present study showed a negative linear relationship with weekly volume (i.e., training and match incidence and burden dropped as the mean weekly training volume per player over the two seasons increased). These findings are contrary to previous studies assessing training and match volume and injury risk in elite Rugby League (Gabbett, 2004a; Gabbett, 2004b). For instance, Gabbett, (2004b), assessed the influence of pre-season training volume, intensity and load on training injury rates in Rugby League players. A significant positive relationship between the incidence of training injuries and training volume, intensity and load was reported. Authors concluded that reducing training volume and intensity could decrease player load, and that incorporating both into a Rugby League training programme could reduce training injury rates. Furthermore, Gabbett, (2004a) reported a significant positive relationship between the incidence of training and match injuries and the volume, intensity and load of training and match play. Both of these studies included all medical attention and time-loss injuries however, nor did they account for the influence of weekly training volumes on injury, and players were monitored over shorter periods of time (pre-season training and 1 season of data, respectively).

More recent studies have reported similar findings to the present study (Ball *et al.*, 2018; Murray *et al*., 2017a; Windt *et al.*, 2016). Windt *et al.* (2016), reported that greater pre-season participation was associated with a decreased likelihood of injury throughout the competitive season for both current and subsequent weeks. Similarly, Murray *et al*. (2017a), reported that elite Australian Football players that completed a greater proportion of pre-season training had higher pre-season training loads, which were positively associated with higher in-season load and player match availability. Authors suggested that players with inadequate pre-season training exposure (<50%) may have failed to elicit the training-induced adaptations needed to prepare players for the demands of match play. In addition, Ball *et al.* (2018), found no significant relationship between overall training load and match injury incidence in University Rugby Union players, but noted that higher weekly training volume in the Backs was associated with significantly lower match incidence rate (p = .007). Authors concluded that maintaining higher training loads allowed players to better prepare for match play without increasing injury risk.

When investigating the influence of training volume on training and match injury risk, the methodological approaches adopted are likely to influence findings. Brooks *et al.* (2008) investigated the influence of weekly training volume on training and match injury risk over two seasons, and reported no relationship between weekly training volume and injury incidence. A noteworthy difference between the current study's findings and Brooks and colleagues (2008), was that the authors reported the lowest incidence rates for their lowest weekly training volumes group (< 5 hours per week). The present study reported the lowest weekly training volume group (< 5.8 hours) to have the greatest training and match incidence rates. In fact, the training incidence rate was ~ 3 times greater for players in the lowest weekly training volume group in the current study compared to Brooks *et al.* (2008) (7.6 vs. 2.4 training injuries per 1000 training hours, respectively). These differences are attributed to two main factors: (1) Brooks *et al*. (2008), excluded recovery sessions from their analysis, whereas the present study did not. The fact that RTP (return to play) sessions were included would have increased the likelihood that low volumes resulted in higher injury incidence in the present study; (2) the current study assessed mean weekly training volumes over the course of two seasons, and therefore report findings more associated with chronic loading. Brooks *et al.* (2008), assessed the influence of weekly fluctuations on injury, and therefore present the effects of more acute loading.

The second factor (i.e., acute vs. chronic volume analysis), may explain why the training and match incidence rates were much lower for Brooks *et al.* (2008), even though their weekly training volume quintiles had a much greater range (< 5 hours per week – 9.1 hours per week). In addition, this may also explain why we reported that players with the highest weekly training volume (> 7.2 hours per week in this study), had the lowest training and match incidence and burden rates (i.e., because these players were likely the most robust and healthy, and could thus complete much higher average training volumes over the course of a season), whereas Brooks *et al*. (2008), reported that players in the highest weekly training volumes (> 9.1 hours), had significantly higher match severity (i.e., these players may have been exposed to a 'spike' in volume, resulting in a greater injury risk because they were not prepared for this increased training demand). Indeed, similar findings for acute increases in volume have been reported previously. For instance, Brooks *et al.* (2006b), investigated the influence of increased training volume the week before match play on hamstring injuries. Authors reported that increased training volume the week before match play was positively associated with hamstring injury rates, and that these were particularly prevalent for major severity injuries. In line with these observations, Kemp *et al.* (2016), also reported that high 1-week training volumes increased injury risk, but that high chronic loading was protective against injury risk (Cross *et al.*, 2016).

3.4.3 Match Exposure and Injury Risk

In the present study, player incidence rates were higher for players who performed in < 15 matches in a 12-month period, but was reduced for players who were exposed to > 15 matches. In addition, incidence was lowest for players who were exposed to > 25 matches over a season. There was a considerable decrease for player match burden when players were involved in 20 matches or more over 12-months. Similar findings have previously been reported in elite Rugby Union. Williams *et al.*, (2017b), reported that players who have been involved in less than 15 matches over the previous 12-months were more susceptible to injury than players with higher chronic match exposure. The authors also noted that players who were involved in > 35 matches over a 12-month period were at the upper limit for professional Rugby Union players, as injury risk became much greater. Williams *et al.*, (2017b), also reported a positive linear relationship between 30-day FGEs (full-game equivalents) and match injury risk, suggesting that accumulated match exposure of a 12-month period may protect against injury, whereas higher exposure over a short period of time may increase risk.

Carling *et al.* (2017), have also shown the negative effects of high match exposure over a short period. Running related performance was severely deteriorated when match exposure was high in their Under 20 Rugby Union cohort. Back players who were exposed >75% of the tournament playing time, and were exposed to > 75 minutes in the final 3 matches of an intensified tournament, showed moderate-to-large decreases in total and high metabolic load distance; high-speed distance in Forwards also showed a similar reduction. Similarly, Phibbs *et al.* (2018), reported that match frequency can have a substantial effect on perceived player-loads (sRPE); players reported considerable increases in 2-week loads when match frequency was increased. These findings suggest that greater match exposure may increase exercise-induced fatigue, which consequently may increase injury risk. However, Carling *et al.* (2017) and Phibbs *et al.* (2018), reported data on adolescent Rugby Union players who likely cannot cope with the demands of higher frequency and match exposure as well as professional players.

The results of the present study suggest that players who engage in appropriately high match exposures are better able to cope with these match demands. Players with greater match exposure sustained far less injuries relative to the volume of time they are on the field for, likely due to greater match fitness and physical robustness (Williams *et al.*, 2016). Reaching an appropriate training and match stimulus may also take time however, and should be gradually and systemically increased if fatigue and injury risk are to be minimised (Gabbett *et al.*, 2016a).

3.4.4 The Influence of Cumulative Training Volume on Injury Risk

In the present study, players were monitored over short weekly cumulative (e.g., 1- and 2-weekly) and long weekly cumulative (e.g., 3- and 4-weekly) periods of time. In the present study, players who were exposed to intermediate-low and very-high 1- and 2-weekly cumulative volumes had a significantly higher injury risk compared to the reference group. Using sRPE, Malone *et al.* (2017b), also reported that professional soccer players who exerted 'intermediate-low' (second lowest workload group in their study, 1500 to ≤ 2120 AU) and 'very-high' (highest load group in their study, > 3200 AU) 1- and 2-weekly workloads had a significantly higher injury risk than the reference group. Similarly, Bowen *et al.* (2017), who investigated accumulated workload in elite youth footballers, reported that high 1-week training loads (total forces exerted on the player over the entire session based on accelerometer data) were significantly associated with an increased injury risk for both overall and non-contact injuries. From a team contact sport perspective, Rogalski *et al.* (2013), reported that elite Australian Football players who exerted very high 1- and 2-weekly loads (>1750AU and 4000AU, respectively), had a significantly greater risk of injury compared to their respective reference groups (< 1250AU and < 2000AU; ORs = 2.44 [95% CI 1.28–4.66] and 4.74, [95% CIs 1.14–19.76], respectively). In elite Rugby Union, Cross *et al.* (2016), reported that increases in 1-weekly loads was linearly associated with increased injury risk. Although speculative, it may be that players with low training volumes simply do not train enough to elicit significantly greater injury risks compared to the reference group, in comparison to players with an 'intermediate low' training volume.

Rogalski *et al.* (2013), and Cross *et al.* (2016) both reported a high change in load from the previous to current week (>1250AU, and > 1069AU, respectively) increased injury risk. Likewise, Malone *et al*. (2017b), reported that players with high 2- and 3-weekly workloads were at an increased injury risk if their previous to current week change was higher (>350 to 550) than the reference group (<200 AU). There was no association between weekly changes in volume and injury risk in this study. This is likely attributed to the load measures used between the current study (volume) and the aforementioned studies (sRPE). Changes in volume (i.e., the present study) do not necessarily mean changes to workload intensity. Therefore, it may be that when players were subjected to a large change in volume, the intensity of these sessions were altered to prevent any substantial increases in injury.

Intermediate-low and intermediate-high 3-weekly cumulative training volumes put players at a significantly greater risk of injury compared to the reference group in this study. There was also a trend towards players with very high 3-weekly cumulative volume having a significantly increased injury risk ($p = 0.06$). Malone *et al*. (2017b), reported that players who exerted pre-season 3-weekly cumulative ≥ 9154 AU were also at significantly higher risk of injury. In addition, Bowen *et al.* (2017), reported that 3-weekly accelerations > 9254 were the strongest indicator of injury risk. Together, these findings suggest that players cannot develop physical robustness needed to cope with increasing training and match demands over 3-week periods. Gabbett *et al*. (2016a), suggested that gradual and systematic increases in load are needed until players adapt to the training stimulus. Indeed, Malone *et al*. (2017b), found that 2-weekly (≥ 5980 AU) and 3-weekly (≥ 9154 AU) workloads in the in-season phase had reduced risk compared to similar loads in the pre-season phase (in-season 2-weekly OR = 0.74, 95% CI: 0.24 to 2.66; in-season 3-weekly = 0.91, 95% CI: 0.26 to 3.14). Furthermore, Colby *et al.* (2017a), reported that very high total distances in the early pre-season for Australian Footballers drastically increased injury risk (> 170 km, OR = 3.2 [95% CIs: 1.3 – 8.5], $p < 0.05$), but that very-high total distance in the late pre-season trended towards a significant reduction in injury risk (> 184 km, OR = 0.3 [95% CIs: 0.1 – 1.0], $p = 0.06$). These findings suggest that the protective effects of higher loads can be achieved in team sports, but only when players have been gradually and systematically exposed to greater loads over time.

3.4.5 The Acute: Chronic Workload Ratios and Training and Match Injury Risk

There was no association with the weekly coupled or uncoupled ACWR method on injury risk in this study ($p > 0.05$). In addition, the mean values for the low through to high groups in this study were very similar for both the coupled and uncoupled methods. Only the very high group showed any true difference between the two mathematical calculations (coupled ACWR = 2.1 for very high; uncoupled ACWR = 2.8 for very high). Previous research conducted by Lolli *et al.* (2017), have shown mathematical coupling when using the weekly coupled rolling average method. The authors highlighted that a spurious correlation between acute and chronic training load estimates exists because the acute load represents a term in the chronic load calculation. The acute and chronic elements of the calculation are therefore not distinct from one another, and thus, the coupling of these functions can actually alter the ACWR. This in turn, provides a biased and invalid metric (Lolli *et al.*, 2017). Regardless, the findings from this paper highlight the inadequacy of using weekly rolling ACWRs, whether these are coupled or not. Menaspà, (2017), has previously highlighted issues regarding the use of rolling averages to monitor injury risk. Rolling averages do not account for the daily variations associated with training and importantly, fail to consider when an athlete was exposed to/recovered from a given stimulus (Menaspà, 2017). Therefore, the use of daily calculations have been shown to be far more superior when investigating injury risk via ACWRs, particularly the use of the EWMA ACWR (Murray *et al*., 2017b).

A recent study conducted by Murray *et al*. (2017b), showed that EWMA for ACWR calculations can provide a more sensitive indicator of injury likelihood, compared to the rolling average method. For very high ACWRs (i.e., > 2.0), both the EWMA and rolling models demonstrated significant associations with injury risk for total distance and high-speed running, however the variance explained by each ACWR model was significantly greater using the EWMA model. Similarly, both the EWMA method and the rolling average method demonstrated significant associations with increased injury risk in our study. The greatest difference between the two methods was that players with an intermediate-low EWMA ACWR trended towards a significantly lower injury risk compared to the reference group ($p = 0.06$), whereas the rolling method showed a positive, linear relationship. This may be due to the rolling method failing to account for the decaying nature of a training stimulus over time. It should be noted however, that both models have shown similar results particularly when assessing workload 'spikes' (Bowen *et al.*, 2020; Hulin *et al.*, 2016a; Warren *et al.*, 2018).

An important finding in the present study was that when acute volume was increased beyond a players already acquired chronic volume, a linear increase in injury risk was apparent (i.e., as the ACWR increased above 1.00, so did injury risk). This was also reported by Cummins *et al.* (2019), in elite Rugby League players. The authors reported that increases in the ACWR > 1.00 for volume were also associated with a linear increase in injury risk. Previous studies looking at measures of intensity however, have reported non-linear relationships. Malone *et al.* (2017b), reported that players who exerted in-season ACWRs of >1.00 to <1.25 were at significantly lower risk of injury compared to the reference group of ≤ 0.85. Whereas Gabbett, (2016a), used internal and external load from different sports (cricket, rugby and Australian football), and reported that ACWR values between 0.8 – 1.3 could reduce injury risk across multiple cohorts. This ACWR range was termed the 'sweet spot'. Our current findings, together with previous results suggest that increased training intensity without altering volume may allow for training-induced adaptations to take place whilst still allowing for appropriate recovery periods. Thus, acute changes to intensity are likely more beneficial than increased training volume when trying to elicit the adaptations needed to cope with the demands of match play. Nevertheless, a gradual and systematic increase in training volume over time will allow players to develop resilience to higher chronic training volumes which may be protective against injury risk.

3.4.6 Methodological Considerations and Limitations

There are methodological considerations and limitations associated with the calculations used in this study that must be discussed. Firstly, Lolli *et al.* (2019), has previously highlighted issues with the ACWR. The authors reported trivial within-subject correlations between acute and chronic load, and found a large and inverse within-subject correlation between the ACWR and its chronic load denominator. Meaning that when prior chronic loading was high, biased (low) acute loads were apparent and vice versa. Authors suggested that acute values alone may be all that is needed, as bias will naturally occur, particularly when there is a trivial association between the numerator (acute load) and denominator (chronic load). Furthermore, Impellizzeri *et al.* (2020), reported that although adaptations of ACWR have been proposed (e.g., weekly vs daily calculations, EWMA, Coupled or Uncoupled), they are all ratios, and, as highlighted by Lolli *et al*. (2019), ratio's fail to normalise the numerator by the denominator and adds unnecessary noise. This has been largely ignored by researchers assessing injury risk in team sports (Impellizzeri *et al.*, 2020; Lolli *et al.*, 2019). Impellizzeri *et al.* (2020), used previously published data and created an artificial ACWR by dividing acute load by fixed and randomly generated chronic loads, and compared results to real data via previously published modelling approaches. Regardless of whether the original analyses was used or the acute load was divided by fixed and randomly generated chronic loads, both showed effects compatible with higher injury risk. The authors also noted that the ACWR magnifies the effect estimates of acute load and decreases the variation, in turn inflating the OR associated with increased injury risk for the numerator alone. Together, these studies question the utility and validity of ACWR calculations, irrespective of where data is coupled or uncoupled, rolling or exponentially-weighted.

An important point to consider when evaluating these results was the inclusion of rehabilitation sessions, as this likely inflated the injury risk associated with lower training volumes. Excluding data beyond the point of injury until that player can return to full training (and is available for match selection) is important to fully understand the injury risks associated with lower 'chronic' training volumes. The lack of other external load measures also limits the findings of this study. The use of 'intensity' measures for training and match play would have been helpful in quantifying the overall load placed on players during training and match play, and would have allowed the differences associated with variations in volume vs. intensity on injury risk to be further explored.

3.4.7 Conclusion

The findings in this study provide a number of important considerations for coaches and practitioners involved in team sports. Players with a consistently high training volume (~ 7 hours per week) had, on the most part, reduced training and match incidence and burden rates compared to lower volumes. This was also apparent for players with higher training volumes, even when between match recovery periods were lower. Therefore, we report that monitoring training volume is crucial for injury risk reduction in elite Rugby Union players. Players who were involved in < 15 matches over a 12-month period had higher match and burden rates, whereas players involved in > 25 matches had the lowest match incidence and burden rates. Very high chronic training volume (> 33.54 hours) over 4-week periods were not significantly associated with increased injury risk, whereas very high training volumes for shorter cumulative periods (1-weekly = > 9.61 hours; 2-weekly = > 17.66 hours) may elicit a greater injury risk. This study shows that even small increases in training volume may increase injury rates. Therefore, the intensity of training may need to be increased whilst still allowing for appropriate recovery before increasing training volume. Indeed, players who are capable of withstanding higher training volumes (~7 hours) per week may be at a reduced risk compared to players with lower volumes. Importantly, the methodological approaches adopted by researchers when investigating load in elite sports such as Rugby Union, Rugby League, Australian Football etc. should be clearly defined, as the results presented will be directly influenced by the methodology used. Indeed, this makes it difficult to recommend the best approach to scientifically evaluate the load-injury relationship in elite Rugby Union. We provide findings that highlight the importance of utilising training volume as a risk factor for injury in Rugby Union. Nevertheless, a limitation of this study was the lack of an intensity measure. Indeed, beyond training and competition volume/exposure, measures of intensity (e.g., GPS and IMU data) will further add to our understanding of the issues surrounding player load and injury risk in elite Rugby Union.

CHAPTER 4A

The Interunit Reliability of Two 10-Hz Global Positioning System Devices to Report Total Distance during Rugby Union Pitch-Based Training

4A.1 INTRODUCTION

The use of Global Positioning Systems (GPS) devices to measure and reliably monitor team sport athletes is well established (Gray *et al.*, 2010; Jennings *et al.*, 2010; Johnston *et al.*, 2012, 2014b; Macfarlane *et al*., 2015; Rampinini *et al.*, 2015; Muñoz-Lopez *et al.*, 2017; Hoppe *et al.*, 2018). These devices are considered best practice when monitoring team sport athletes due to the ease of data collection and the quality of the data provided (Hartwig *et al.*, 2011; Gabbett *et al.*, 2012). They allow coaches and practitioners working in elite team sports to quantify the movement demands of both match play and training. In turn, match play data can be used to develop position specific performance profiles that assist in the structuring and adapting of training programmes (Hoppe *et al.*, 2018), whereas the monitoring of pitch-based training sessions allows for periodisation strategies to be implemented on a daily basis (Hoppe *et al.*, 2018).

The vast majority of studies that have investigated the use of GPS devices to measure and reliably monitor team sport athletes have used various criterion measures in which to compare the GPS data (Beato *et al.*, 2016; Jennings *et al.*, 2010; Johnston *et al.*, 2012, 2014b; Roe *et al.*, 2016a; Thornton *et al.*, 2019). For example, studies have used known distances combined with timing gates (Coutts and Duffield, 2010; Jennings *et al.*, 2010; Johnston *et al.*, 2012, 2014b; Hoppe *et al.*, 2018), motion capture systems (Hartwig *et al.*, 2011; Roell *et al.*, 2018), and laser/radar (Varley *et al*., 2012; Rampinini *et al.*, 2015) derived velocities as criterion measure. A common finding between studies is that total distance is one of the most accurately and reliably measured metrics (Jennings *et al.*, 2010; Rampinini *et al.*, 2015; Thornton *et al.*, 2019). Manufacturing devices housing lower sampling frequencies (1-5 Hz) have been shown to limit the utility of these devices, particularly when the distances measured involve short accelerated runs, higher velocities or changes of direction (COD) (Jennings *et al.*, 2010). An established finding is that 10 Hz devices have largely overcome the limitations associated with lower sampling frequencies (Macfarlane *et al*., 2015). It has also been reported that 15 Hz devices do not significantly improve collected data compared to 10 Hz devices (Johnston *et al.*, 2014b), suggesting that teams using 10 Hz devices can be confident that the derived data is both valid and reliable.

An important point of consideration when conducting research that involves the collection of GPS data, is that studies which are able to include multiple teams across multiple seasons are likely to report findings that are more generalisable across the sport, (rather than findings associated with the team involved in that particular study). Multi-team and multi-season studies are thus more useful for team coaches and practitioners exploring the literature for ways in which they can improve their monitoring, and in turn, optimise performance and minimise injury risk through GPS derived measures. However, if the movement demands investigated in these studies are collected from teams using different GPS devices, then combining or comparing data prior to assessing the interunit reliability of the devices would be poor practice. Interunit reliability refers to the ability of multiple devices to produce the same measure for the same experimental protocol (Macfarlane *et al*., 2015). Therefore, if teams use different devices, it is vital that good interunit reliability is shown, otherwise the comparison of player training and match data may be invalid. In this case, investigating the data between different devices holds the same scientific relevance as intraunit reliability (Macfarlane *et al*., 2015), which has been scientifically evaluated to a much greater extent (Macfarlane *et al*., 2015).

Studies that have investigated the validity and reliability of 10 Hz GPS units to measure total distance have improved from simply straight line running (Castellano *et al.*, 2011), to more 'game-specific' circuits (Johnston *et al.*, 2014b). Indeed, ensuring that data is collected by incorporating as many aspects of training and match scenarios as possible is important. However, there are aspects of Rugby Union training and match play that have not been considered when testing the reliability of these devices to measure total distance. The short accelerated runs and quick changes of direction over a training session or match, coupled with contact events such as tackling, scrummaging, rucking and mauling may further hinder the reliability between devices, due to the stop and start motion of these aspects of play.

Within Chapter 4B, two of the most commonly used and commercially available GPS units were used (Catapult Optimeye S5 and GPSports EVO 10 Hz devices) to monitor training and match volume and total distance. Therefore, the aim of the present study was to investigate the interunit reliability of these devices to report total distance over Rugby Union pitch-based training sessions. This was to ensure the data derived from both devices were reliable and showed good agreement, and thus the teams involved in this study could be monitored, and the findings presented valid. It was hypothesised that there would be no significantly relevant difference between the two devices to report total distance during Rugby Union training, which incorporated all aspects of training and match play scenarios (e.g., scrummaging, rucking, mauling, tackling, sprints, accelerations etc.).

4A.2 METHODOLOGY

4A.2.1 Participants

Seventeen male senior Rugby Union players from the Edinburgh Academical Football Club (23.4 ± 4.1 years, 93.8 ± 13.3 kg, 182.2 ± 6.8 cm) volunteered to participate in this study. All participants were active and competitive Rugby Union players with multiple season's worth of experience. Prior to participation in the study, all participants were asked to read the study information sheet, which highlighted the reasons for the study, and what participants could expect from participating in the study. All participants were given the opportunity to ask questions prior to providing written informed consent.

4A.2.2 Experimental Procedures

All testing sessions were conducted in the afternoon, as this was the designated training time for the club involved. Prior to commencement of each training session, 10 players were randomly selected to wear two GPS units in a customised dual-pouch vest (one of each manufactured device, see Figure 4A.1). A maximum of 10 players participated in the study at any one time due to there being 10 dual pouch vests. However, because not all players could make every training session, a total of 17 players were involved in the study. The GPS devices used were 10 Hz Catapult Optimeye S5 devices (Catapult, OptimeyeS5, Melbourne, Australia) and 10 Hz GPSports EVO devices (GPSports, EVO units, Canberra, Australia). Four training sessions were completed in total based on the power and sample size calculation outlined in section 4.2.5.

On arrival at the club all units were checked to ensure each was fully charged. Thereafter the units were switched on and left outside to establish a satellite connection prior to commencement of each training session. The units were kept stationary to pick up as many satellites as possible and to reduce the horizontal dilution of precision (HDOP). Participants were then fitted with an appropriately sized custom-made dual-pouch vest underneath their playing jersey. Participants were given a set size in order to minimise movement of the unit whilst in the pouch during exercise. Each participant was then fitted with one of each device. Both units sat on the upper thoracic spine between the scapulae. The positioning of the units were randomly allocated so that 5 participants wore the Catapult unit on the right side and the

GPSports unit on the left side, and vice versa for the remaining 5 participants. This was done for each individual training sessions.

Figure 4A.1: Dual pouch vests used to collect total distance data during Rugby Union pitch-based training.

4A.2.3 Training Sessions

All testing sessions were carried out on the Edinburgh Academical Football Club grass pitch, which is clear of large buildings or structures that may have obstructed the satellite reception. Once 10 participants had been fitted with each device, a warm-up was completed by the strength and conditioning coach assigned to the club. Thereafter, the team coaches ran through their planned training session for that day. This included speed/power work, skills, general play/phase work, set-piece work, scrummaging… amongst other Rugby Union specific drills that are typical at the elite level. Sessions lasted approximately 1.5 hours each (18:45pm – 20:15pm). On completion of the training session the units were removed from each dual-pouch vest, turned off and analysed the following day.

4A.2.4 Data Analysis

The GPSports units were downloaded using the GPSports EVO cloud, and the Catapult units were downloaded using Catapults Openfield Software. Once the data from all 20 units had been downloaded, the start and end times were manually inputted from the beginning of the warm up until completion of the training session. The data was then fast baked and exported into a raw Configurable Team Report (CTR) file in excel. The total distance covered by each player was then taken from the raw exports, and the units worn by each player were compared. In total, 80 datasets were collected throughout the study (10 of each unit per session over 4 training sessions, giving 40 Catapult datasets and 40 GPSports datasets). There was an issue with one of the GPSports units during the 2nd testing session however. Therefore, the training data for that participant was excluded from the analysis, giving 78 datasets in total. This was an appropriate number of samples, given the sample size calculation presented in section 4.2.5.

The HDOP was exported from Openfield at the end of each session so that the accuracy and quality of the satellite reception could be assessed. The HDOP is reported so that internal validation can be made for each GPS units recording. The accuracy and geometric quality of a GPS satellite configuration is measured through the HDOP. The smaller the HDOP value, the better the geometry. The HDOP will vary depending on the number and location of satellites in the sky, and their position in relation to the unit for sending and receiving signals. If satellites are well spread out, the HDOP will be low and precision high. If the satellites are clustered however, then the HDOP will be high, and precision low (Malone *et al.*, 2017a) (See Figure 4A.2A and 4A.2B). Values can range from < 1 to a maximum of 50 (Jennings *et al.*, 2010). A HDOP of 1 is considered ideal, and < 1 very good (Jennings *et al.*, 2010). As values increase, the position fix becomes increasingly unreliable. In fact, GPSports internal code for SPI Pro units has previously been reported to automatically reject data with HDOP values >4 (Linke *et al.*, 2018), as the position fix by this point is entirely unreliable.

Within the present study, if the HDOP values were below < 1 (i.e., very good) and a minimum of 6 satellites were connected, then the data were included. If less than 6 satellites were connected, or the HDOP was > 1, then the data was excluded. Fewer than 6 connected satellites can result in a poor position fix, which in turn implicates the quality of the data (Malone *et al.*, 2017a).

A

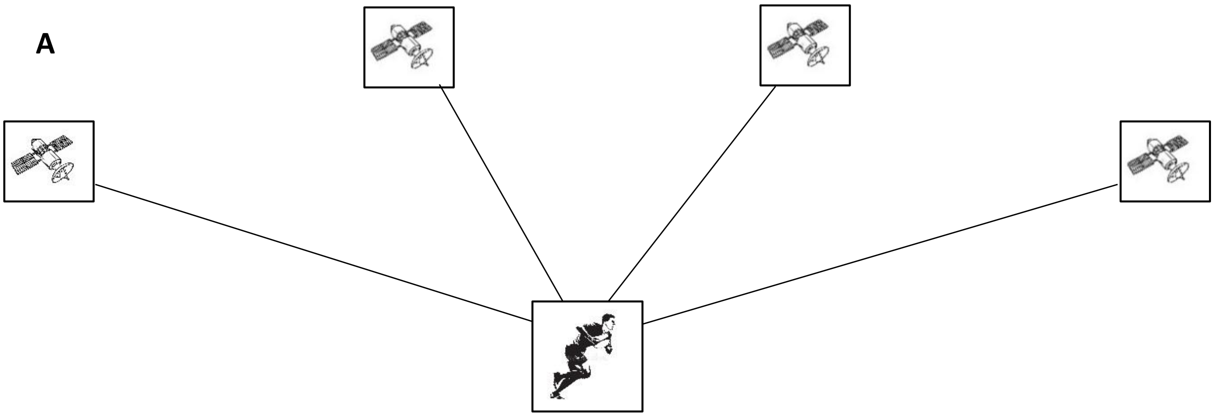


Figure 4A.2A: Well-dispersed satellites will reduce horizontal dilution of precision and give more accurate results.

B

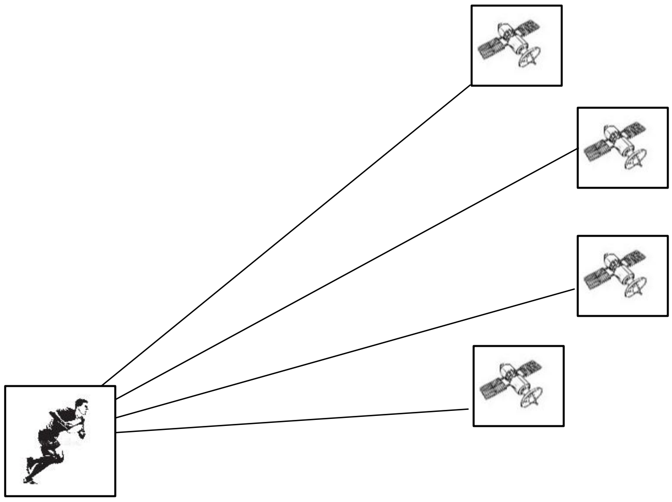


Figure 4A.2B: Clustered satellites will increase horizontal dilution of precision and give less accurate results.

4A.2.5 Power and Sample Size for Total Distance

To prevent a type I or type II error occurring, a power and sample size calculation was conducted. The calculations were based on previous datasets collected by Johnston *et al.* (2014b), and Johnston *et al.* (2012). The study conducted by Johnston *et al.* (2014b) compared 10 Hz Catapult Units (MinimaxX S4, 10 Hz, Firmware 6.70, Catapult Innovations) and 15 Hz GPSports units (SPI-ProX, 15 Hz, Firmware V2.4.3, GPSports), whereas Johnston *et al.* (2012), compared 5 Hz Catapult Minimax units (Team Sport 2.5, 5 Hz, Firmware 6.54, Catapult Innovations, Melbourne, Australia) only. The data for the present study's sample size calculation was estimated from both Johnston *et al.* (2012), and Johnston *et al.* (2014b), using the 'total distance' variable in each of the previous studies. These calculations were performed on G*Power (G*Power, 3.1.9.2, Germany) (Faul *et al.*, 2007, 2009), and the type of analysis ran on the dataset was a priori sample size calculation.

Firstly, power and sample size were estimated from Johnston *et al.* (2014b). The Minimax device reported a mean total distance (TD) of 1326 m (± 24.6 m), compared to GPSports mean TD of 1301.8 m (± 26.1 m). The input parameters were a 2-tailed test, with effect size = 0.95, alpha = 0.05, power = 0.8. The sample size needed to achieve a minimum of 80% power was 11 participants. The same calculation was then ran on the data reported by Johnston *et al.* (2012). The mean TD for the Minimax unit 1 devices was 1309 m (± 51 m) and 1329 m (± 42.6 m) for the Minimax unit 2 devices. The sample size needed to achieve a minimum of 80% was 46 participants. Given the moderate to large discrepancy between the two calculations, we aimed to complete four testing sessions with 10 individuals (giving 40 datasets for comparison). On completion of the four sessions, a retrospective calculation was completed to test for power and sample size. The effect size was calculated as 0.66 (Catapult mean TD = 4163m (± 828 m); GPSports mean TD = 4050 m (± 860 m); correlation between the two groups = 0.98). Inputs parameters included a 2-tailed post hoc test, with an effect size of 0.657, alpha = 0.05, total sample size = 39. The power was calculated as 97.9%.

4A.2.6 Statistical Analysis

The present study was designed to assess the interunit reliability of two GPS devices during Rugby Union specific training. Therefore, there was no 'gold standard' criterion or 'true value' to compare the units against. Comparisons were made only on the reliability of the devices to report the same distance covered by the same player during Rugby Union pitch-based training. On completion of the analysis, normality was assessed using a Shapiro-Wilks test. Intra-class correlation coefficients (ICCs) were used to assess the relationship between the two units, and the relative typical error (TE) was calculated as a coefficient of variation (CV). The CV was calculated because the HDOP and satellite count were unavailable for testing session 1, and therefore, the trial-to-trial reliability of the units to report the same distance for the same athlete was expressed and rated by the magnitude of the CV (Hoppe *et al.*, 2018). This ensured all testing sessions provided similar results, and thus all sessions were included in the analysis. However, there is no consensus regarding statistical thresholds that would indicate acceptable reliability in this field of research (Macfarlane *et al.*, 2015; Hoppe *et al.*, 2018). Therefore, reliability was rated as good (CV: 0 to <5%), moderate (CV: 5 to <10%), and poor (CV: >10%), (Macfarlane *et al.,* 2015). As linear association (assessed via the ICC) cannot automatically imply good agreement between the two units, a Bland-Altman Limits of Agreement plot was also constructed. Given there is no consensus regarding statistical thresholds that would indicate acceptable agreement, maximal acceptable limits were defined *a priori*, based on findings by Castellano *et al.* (2011) and Johnston *et al.* (2014b), who reported < 5% CV during straight line running and moderate to high speeds, but a typical error of measurement of 11.5% for very high speeds (Johnston *et al.*, 2014b). Therefore, the maximal acceptable limits were taken as < 10%, given the range of speeds covered over a training session. Linear Regression was conducted to assess proportional bias. Significance was set at the 95th percentile ($p < 0.05$).

4A.3 RESULTS

4A.3.1 Horizontal Dilution of Precision and Number of Satellites

The mean HDOP (± standard deviation ([SD]) for the 2nd, 3rd and 4th testing session during data collection were 0.54 (± 0.09), 0.67 (± 0.19) and 0.57 (± 0.17), respectively. Furthermore, the mean (± SD) number of satellites for the 2nd, 3rd and 4th testing session were 11.94 (± 0.86), 11.86 (± 1.07) and 11.79 (± 1.52). All testing sessions had low cloud coverage on all training sessions except testing session 3, which had heavy cloud coverage. The HDOP and number of satellites could not be retrieved for the 1st testing session. The data was included however, based on an evaluation of the CV (see Table 4A.1), which showed good reliability for all testing sessions (CV < 5%).

Table 4A.1: Interunit reliability (CV %) of GPS devices for determining the distances covered with descriptive data (mean distance, mean difference between the units, expressed in metres and percentage of mean total distance).

Training Sessions	CV (± SD)	Mean Distance (m)	Mean Difference (m)	Mean Difference (%)
Training Session 1	1.4% (± 1.6%)	3917	109	2.8
Training Session 2	2.7% (± 1.7%)	4429	147	3.3
Training Session 3	1.9% (± 1.5%)	4098	126	3.1
Training Session 4	1.2% (± 0.8%)	4013	75	1.9
Total	**1.8% (± 1.6%)**	**4106**	**113**	**2.8**

4A.3.2 Tests of Normality

A Shapiro-Wilks test for normality was run on the dataset for the Catapult Units, GPSports Units and the difference between these units for reporting TD (see Table 4A.2). All tests reported no statistical significance (p < 0.05), and thus all data was considered normally distributed.

Table 4A.2: SPSS output for testing normality of the data set.

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Catapult	.098	39	.200*	.981	39	.743
GPSports	.109	39	.200*	.980	39	.689
Difference	.137	39	.064	.943	39	.050

4A.3.3 Reliability - Intra-Class Correlation Coefficient

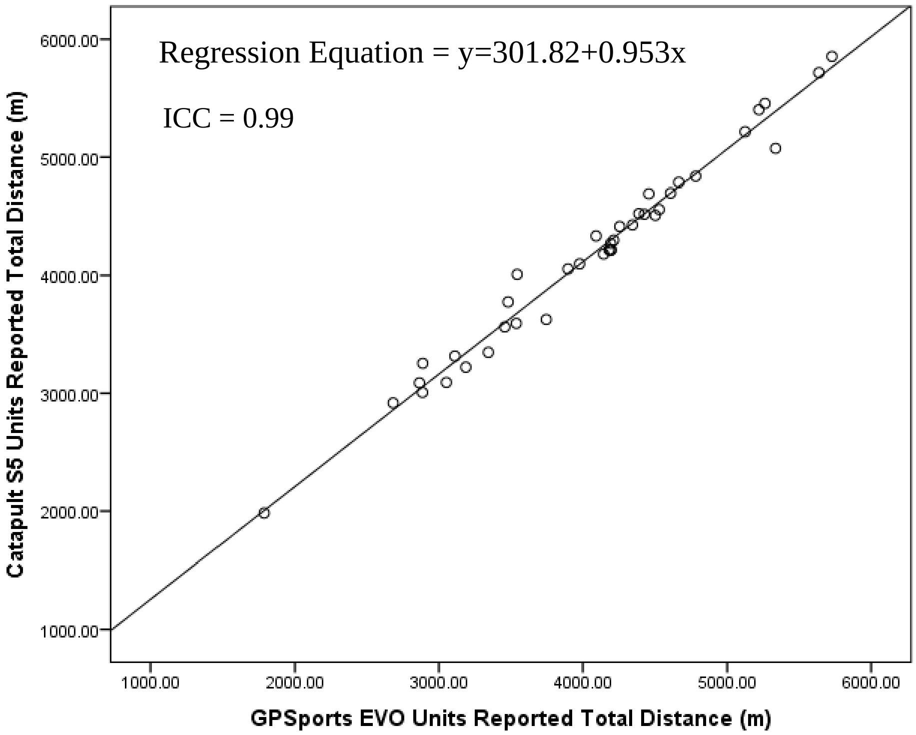


Figure 4A.3: Scatterplot of Catapults Optimeye S5 units vs. GPSports EVO units for reported total distance.

The Intra-Class Correlation Coefficient was examined to assess the relationship between the two devices for reported total distance. The model used was a two-way mixed model, assessing the ‘absolute agreement’ between the two GPS units. An ICC of 0.98 was reported for the individual measures, and an ICC of 0.99 was reported for the average of the measures (see Figure 4A.3).

The Bland-Altman plot statistics, with calculated confidence intervals (95% CIs) for the mean difference and upper and lower limits of agreement were calculated to measure how precise the data estimates were (Giavarina, 2015). The magnitude of the systematic difference, shown by the 95% CI of the mean difference, is from 72.96 m to 153.8 m. The 95% CIs for the upper limit were from 287.19 m to 426.8 m. The 95% CIs for the lower limit were from -60.88 m to -200.8 m. These were measured by using standard error once it was known that the differences followed a distribution that was approximately normal (Giavarina, 2015). Standard error of d was calculated using $\sqrt{s^2}/n$, whereas the standard error of d + 1.96s and d - 1.96s was calculated using $\sqrt{3s^2}/n$ (see Table 4A.3).

Table 4A.3: Bland-Altman plot statistics, including the elements to calculate confidence intervals.

Parameter	Unit	Standard Error Formula	Standard Error (se)	t value for 38 degrees of freedom	Confidence (se * t)	95% Confidence Intervals	
Number (n)	39					From -	to
Degrees of Freedom (n-1)	38						
Difference mean (d)	113.36	$\sqrt{s^2}/n$	19.95	2.025	40.4	72.96	153.8
Standard deviation (s)	124.60						
Upper Limit (d + 1.96s)	357.50	$\sqrt{3s^2}/n$	34.56	2.025	69.98	287.19	426.8
Lower Limit (d - 1.96s)	-130.86	$\sqrt{3s^2}/n$	34.56	2.025	69.98	-60.88	-200.8

4A.3.4 Agreement - Bland-Altman Limits of Agreement

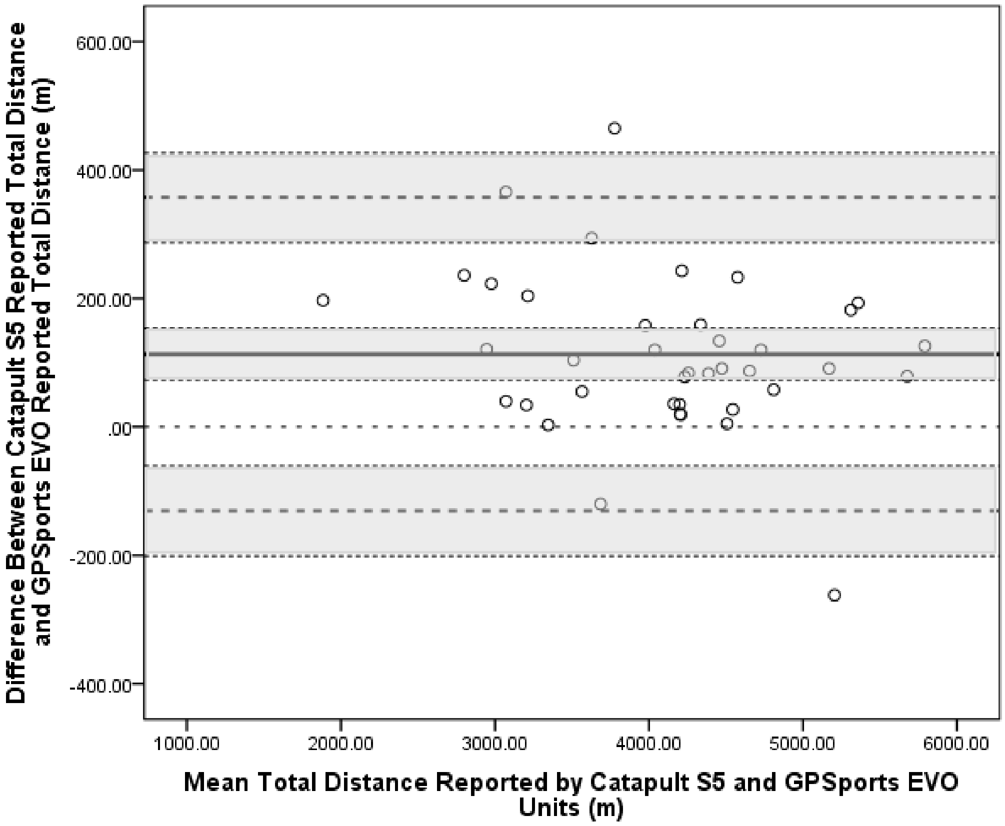


Figure 4A.4: Bland Altman limits of agreement plot for Catapult vs. GPSports units for reporting total distance. The 95% confidence intervals for the mean bias, and upper and lower limits are shaded in grey.

The Bland-Altman plot defines a bias of 113.4 m, and an agreement range from -130.9 to 357.5 m. The 95% CI of the mean difference is from 72.9 m to 153.8 m. The 95% CIs for the upper and lower limits were from 287.2 m to 426.8 m, and -60.9 m to -200.8 m, respectively (Figure 4A.4). Linear regression reported no proportional bias between measurements ($p < 0.05$).

4A.4 DISCUSSION

4A.4.1 Main Findings

This study aimed to establish the interunit relatability between two of the most commonly used GPS devices in professional team sport. The comprehensive evaluation of these 10 Hz devices (Catapult and GPSports) to report total distance during Rugby Union pitch based training demonstrated good interunit reliability across each training session (CV = 1.8%). There was little variation, and a large linear association between devices to report total distance (ICC > 0.9). The Catapult units consistently reported greater total distance compared to the GPSport units, which resulted in a bias of 113.4m (assessed via the Bland-Altman limits of agreement). Nevertheless, the mean difference (taken as a percentage of the mean total distance, 4,106 m) was small (2.8 %), and the maximum limits of acceptable agreement were met (lower and upper limits = 3.2 – 8.7%). There appeared to be a greater bias (i.e., spread of data point beyond the mean bias), when players covered lower distances (3000 – 3,500 m) during training compared to greater total distance (> 4000 m), suggesting that training sessions involving more running related training activities improved the interunit reliability. Linear regression revealed no proportional bias between measurements, suggesting that differences between devices for calculating total distance were small.

4A.4.2 Interunit Reliability for Reporting Total Distance

The HDOP and satellite number could not be retrieved for the first training session completed in this study. Therefore, the trial-to-trial reliability of the units to report the same distance was expressed and rated by the magnitude of the CV, which was < 3% for all testing sessions, and 1.8% across the study. Although often compared to a criterion measure, these findings indicate good reliability between the 10 Hz devices. Previous research using lower sampling frequencies have reported greater error. For instance, Coutts and Duffield, (2010) reported CV values of 4.5 – 7.2% using 1 Hz devices during a running circuit. In addition, very poor interunit reliability was reported for distance when players executed high and very-high intensity running (CV = 11.2 - 32.4% and 11.5 -30.4%, respectively).

Interestingly, Jennings *et al.* (2010) investigated the interunit reliability of two 5 Hz devices over a simulated circuit, and reported that, regardless of velocity (walking - sprinting), there was a greater than 10% difference between devices for all protocols, with the exception of walking between the 20–40 m interval (difference = 9.9%). Total distance over the simulated circuit, however, exhibited the lowest error (CV = 3.6%) (Jennings *et al.*, 2010), suggesting that total distance is one of the most accurate measurements of external load when utilising GPS data. Indeed, Rampinini *et al.* (2015), reported that for both 5 Hz and 10 Hz GPS devices, total distance reported the lowest error during shuttle intermittent running (2.8% and 1.9%, respectively). Furthermore, Johnston *et al.* (2012), who investigated the reliability of 5 Hz devices to report total distance during a simulated circuit, revealed that GPS was a valid and reliable measure of total distance covered ($p < 0.05$, percentage typical error of measurement [%TEM], < 5%). However, Johnston *et al.* (2012) did not assess the interunit reliability, which suggests that 5 Hz units may be able to provide reliable results for the same unit (i.e., interunit reliability may be much poorer than intraunit reliability when lower sampling frequencies are used).

The current study has shown more acceptable interunit reliability compared to lower sampling frequencies (1 – 5 Hz). We report a small difference between the two devices to report total distance (2.8%), and the 95% limits of agreement were within the *a priori* maximal acceptable difference of < 10%. Furthermore, the ICC was 0.98 and 0.99 for relative and absolute measures. Similar to the present study, Castellano *et al.* (2011) reported good interunit reliability for 10 Hz GPS devices when investigating GPS derived total distance over 15 and 30 m running (CV = 1.3 and 0.7%, respectively). Furthermore, Johnston *et al.* (2014b), reported good interunit reliability for total distance (TEM = 1.3%, ICC = 0.51), low-speed distance (TEM = 1.7%, ICC = 0.97), and high-speed distance (TEM = 4.8%, ICC = 0.88). The current study reported much lower variance compared to Johnston *et al.* (2014b), for total distance covered. This may be due to Johnston *et al.* (2014b), using a simulated circuit as a criterion measure, as participants may not have followed the circuit correctly, which would have increased variance in reported distance (Johnston *et al.*, 2014b). There was also poor interunit reliability reported by Johnston *et al.* (2014b) for high (30m) and very high (40m) running distance (TEM = 11.5%) also, suggesting that comparisons between 10 Hz GPS devices during high-speed running (> 14 $km \cdot h^{-1}$) are unadvisable. Of course, high speed running is an inevitable part of training and match play, and such metrics have been used to analyse performance and also investigate causes of injury risk (Colby *et al.*, 2017a; Stares *et al.*, 2018; Bowen *et al.*, 2020). Therefore, the potential limitations of these devices to report high-speed movements have largely been acknowledged. Nevertheless, total distance appears to be a reliable measure for monitoring external load during Rugby Union pitch-based work and may therefore be an important risk factor to investigate when assessing the load-injury relationship in elite Rugby Union players.

4A.4.3 Limitations

A limitation of the current study was that no criterion measure was used, meaning that unlike previous studies assessing the reliability of GPS devices to report total distance (Coutts and Duffield, 2010; Jennings *et al.*, 2010; Johnston *et al.*, 2012, 2014b; Hoppe *et al.*, 2018), we cannot comment on possible under or over-estimation of total distance reported by the 10 Hz units used in this study. A common reporting in this research field is that GPS devices often over-estimate the actual distance covered (Gray *et al.*, 2010; Johnston *et al.*, 2014b). Within the present study, the Catapult units reported greater distance on average compared to the GPSport units. Without a criterion measure however, we cannot comment on which unit was more accurate. Different software programs were used to collect and analyse the GPS data. Although we cannot comment on any possible influence associated with different software programmes, this could have influenced the reported total distance values, and consequently the interunit reliability of the devices used in this study (Johnston *et al.*, 2014b; Thornton *et al.*, 2019). A limitation of this study is that only total distance was investigated, and therefore the interunit reliability associated with other movement demands and external loading indicators cannot be presented.

4A.4.4 Conclusion

This study's findings, in conjunction with previous observations on the ability of GPS units to report total distance, show that different 10 Hz GPS units can reliably report total distance during Rugby Union pitch-based training. Catapult units appear to report higher total distance values compared to GPSport units, which may be due to improved accuracy, however this warrants further investigation. Interestingly, the bias between the units used in this study was lower when greater distances were covered during training (> 4000m). This may be due to set piece, contact work, or interval type training causing more errors in distance reported (i.e., short and/or fast paced movements are likely to report greater error [Jennings *et al.*, 2010]), compared to more running related activities, however this is speculative and requires further investigation. We report that 10 Hz devices have good interunit reliability when measuring total distance (CV = 1.8%), and report small variation (ICC = 0.98 and 0.99). There is a small bias between the units (2.8%), and the upper limits of acceptable agreement were good to moderate (3.2 - 8.7%), which suggests that players wearing different units can be tracked with confidence when using the devices investigated in this study, at least for total distance.

CHAPTER 4B

Quantifying the On-Pitch Demands of Elite Scottish Rugby Union Training and Match Play and its Association with Injury Risk

4B.1 INTRODUCTION

In an effort to strive towards enhanced fitness and performance, athletes need to expose themselves to varying external workloads (e.g., distance ran, time spent at a given velocity, weight lifted…) that push the boundaries of their current physiological capabilities. All injuries however, are sustained under workload (Windt and Gabbett, 2016), meaning exposure to all training and competition loads have the potential for athletic injury, particularly if the given workload is sub-optimal (e.g., too high or too low). Consequently, understanding an athlete's current workload status is important for ensuring appropriate training doses are prescribed that allow for both an improvement in performance, but also a sufficient recovery period (Gabbett and Jenkins, 2011). Insufficient recovery, coupled with further exposure to training or match stimuli will alter the promotion of physiological adaptation to the affected structures, resulting in greater fatigue and a higher risk of injury (Soligard *et al.*, 2016; Andrade *et al.*, 2020). Failure to incorporate these fundamental training aspects into a training programme will have particular consequences on players who are involved in team contact sports like Rugby Union.

Research in elite team sport (i.e., Rugby Union, Rugby League, Australian Football, Soccer, etc.) has focussed on a number of important workload modalities an in effort to optimise performance and minimise injury risk. For instance, the absolute training prescription of athletes over acute (i.e., 1-week), and accumulating periods (i.e., 2-, 3- and 4-weekly absolute workload), as well as the influence of large changes in weekly workload have been linked to injury (Bowen *et al.*, 2020; Colby *et al.*, 2017b; Cross e*t al.*, 2016; Murray *et al.*, 2017c; Rogalski *et al.*, 2013; Stares *et al.*, 2018). It has been reported that higher accumulated workloads may protect players against injury - suggested to be through an enhanced workload capacity, and consequently a greater resilience to injury - whilst lower workloads may fail to elicit the stimuli needed to promote adaptation or result in detraining, consequently increasing injury risk (Gabbett, 2016a). To achieve higher workloads however, increases in load must be gradual and systematic (Soligard *et al.*, 2016), otherwise, players may be exposed to loads they are incapable of withstanding (i.e., spikes in workload) (Hulin *et al.*, 2014; Bowen *et al.*, 2020).

On this basis, there has been a growing support for the acute: chronic workload ratio (ACWR). This relative workload index can be used to investigate what the athlete is currently undergoing (current acute 1-week load), compared to what the athlete has been prepared for (previous chronic 4-week load) (Hulin *et al.*, 2016b).

When investigating load-injury relationships, the use of the aforementioned workload calculations have been used across multiple team sports in conjunction with modifiable external workload variables (e.g., total distance [TD], accelerations, PlayerLoad^{TM}, high-speed running [HSR] distance). These workload-injury relationships have been investigated in multiple non-contact and contact team sports. For instance, Malone *et al.* (2018a), reported that elite Soccer players who had large weekly changes in HSR distance were at greater injury risk than players with similar HSR distance from week to week. In addition, Murray *et al.* (2017c) reported that high acute (1-week) loads for PlayerLoad^{TM} significantly increased injury risk in Australian Footballers, whereas Colby *et al.* (2014), reported that Australian Footballers were significantly more like to be injured when TD, sprint distance and force load were very high over 3-week periods. Recently, research has looked at a player's chronic loading in relation to their ACWR status. A common finding in both non-contact (Soccer and Cricket) and contact team sports (Rugby League), is that when chronic loads are low and the ACWR high, injury risk is elevated (Bowen *et al.*, 2020; Hulin *et al.*, 2016b).

Although these findings have important implications within their sport, the risk factors for one team sport may not necessarily translate into another. Currently there has been no studies investigating the influence of external loads via global positioning system (GPS) and inertial measurement unit (IMU) derived measures (e.g., TD, HSR, PlayerLoad^{TM}, accelerations etc.) using workload calculations (e.g., acute, chronic, weekly changes, cumulative loading) to investigate injury risk in elite Rugby Union. As such, this gap in the literature for Rugby Union specific monitoring needs addressed. Multiple studies have highlighted the risks associated with load and injury in elite Rugby Union in other settings (Brooks *et al*., 2008; Cross *et al.*, 2016; Fuller *et al*., 2010; West *et al*., 2019; Williams *et al.*, 2017b). For instance, Cross *et al.*, (2016), reported a linear relationship with increases in acute load (1-week) and weekly change and injury risk using the sRPE method. In addition, Cross *et al.*, (2016), reported a U-shaped relationship for 4-week cumulative loads, such that intermediate loads (5932–8651 AU) had a likely beneficial reduction in injury risk, whereas high loads (>8651 AU) reported a likely harmful effect. More recently, Weaving *et al.* (2018), conducted a principal component analysis (PCA) following the monitoring of workload in elite Rugby Union players for pitch-based skills training over the course of a season. The authors used GPS (total distance [TD] and individualised high-speed running distance [>61% maximal velocity]) and IMU (PlayerLoad^{TM}) measures to monitor external loads, and showed well-defined relationships with the PC loadings (PC_L) ($PC_L > 0.7$). From the external load measures, TD reported a PC_L of 0.86 to 0.98 and PlayerLoad^{TM} reported a PC_L of 0.71 to 0.98 for the 1st PC. In addition, individualised high-speed running distance captured additional training load information (+19 – 28%), and was the only variable to relate to the 2nd PC (PC_L: 0.72 to 1.00).

Together these findings highlight that pitch-based training load in Rugby Union can be monitored with GPS and IMU derived external load variables, and that well-established workload calculations (i.e., acute, chronic, cumulative metrics) are linked with injury in Rugby Union (Cross *et al.*, 2016; Weaving *et al.*, 2018). Therefore, combining GPS and IMU derived loads with these well-established workload calculations is likely to provide important information regarding the influence of pitch-based load and injury risk in professional Rugby Union players. Indeed, this has previously been shown in other contact and non-contact team sports (Bowen *et al.*, 2020; Colby *et al.*, 2017b; Murray *et al.*, 2017c; Stares *et al.*, 2018). Together these findings highlight that investigating the load-injury relationship in Rugby Union for pitch-based work via GPS and IMUs is important to further understand the influence of Rugby Union training and match play demands on injury risk.

The aim of the current study was to investigate the relationship between GPS/IMU workloads during Rugby Union pitch based training and competitive match play over the 2017/18 (TD) and 2018/19 seasons (all workload variables including total distance) and injury risk in elite Rugby Union players. All training and match workload data were combined to give total loads over each week. In addition, all training and match injury data was combined to assess the influence of overall training and match loads on overall injury risk. In order to achieve this aim, the following objectives were carried out:

- Investigate the load-injury relationship for each specific GPS/IMU variable, as commonly done when assessing workload and injury risk in team sports.
- To provide a comprehensive analysis of how external GPS and IMU loads can influence injury risk via acute, chronic, cumulative, weekly changes and ACWR metrics in elite Scottish Rugby Union players.

It was hypothesised that:

- There would be significant associations between workload data and injury risk
- Positional differences would exist for workload calculations and this would impact the associated GPS/IMU workload-injury risk (see Appendix F for supplementary data).
- Low chronic load combined with higher ACWR values would be a sensitive measure for injury risk analysis.

4B.2 METHODOLOGY

4B.2.1 Study Design and Participants

This prospective cohort study monitored the on-pitch training and match demands in elite Scottish Rugby Union (SRU) players from the SRUs professional men's 15-a-side teams (Edinburgh Rugby, Glasgow Warriors and Scotland International). Data collected from players who were not training or playing at the professional level, or who were under 18, were discarded from this study. The total distance (TD) data - which following Chapter 4A - was collected over two seasons (2017/18 and 2018/19 seasons). Over the 2017/18 and 2018/19 seasons, a total of 141 players were involved in the study (Backs = 62; Forwards = 79). Of these 141 players, 31 were involved in the 2017/18 season only (Backs = 14; Forwards = 17), 25 were involved in the 2018/19 season only (Backs = 8; Forwards = 17), and 85 players were involved in both seasons (Backs = 40; Forwards = 45). For all other load-monitoring variables (high-speed running [HSR] distance > 5.0 meters per second [m·s], relative distance > 60% of maximum velocity, relative distance > 80% of maximum velocity, acceleration meters >2 $m \cdot s^{-2}$, acceleration meters >3 $m \cdot s^{-2}$ and PlayerLoad™), data were collected over the 2018/19 season only. A total of 110 players were involved in this part of the study (Forwards = 62; Backs = 48). Player data for the two-season and one-season analysis are presented in Table 1.

Table 4B.1: Player information relating to players involved in the two-season analysis for total distance and one-season analysis for all other workload variables (high-speed running distance [HSR], relative distance > 60% of maximum velocity, relative distance > 80% of maximum velocity, acceleration meters >2 $m \cdot s^{-2}$, acceleration meters >3 $m \cdot s^{-2}$, PlayerLoad™).

Results Section	Players (n)	Age (y)	Body Mass (kg)
Total Distance (2017/18 and 2018/19)	141	27.9 (± 3.9)	104.1 (± 12.5)
Remaining Workload Variables (2018/19)	110	27.4 (± 3.7)	104.4 (± 13.0)

NOTE: n, number of players involved in the study; y, years; kg, kilograms

4B.2.2 Data Confidentiality

As per Chapter 3, unique player codes were used for all players to ensure confidentiality and anonymity across all team databases. All codes were password protected and only the researcher could access these. Player codes were consistent across seasons and databases, allowing cross checked to be conducted without putting player information at risk.

4B.2.3 Quantifying External Workload

Similar training and match definitions used in Chapter 3, Study 1, were used in the current study. This particular study only included pitch-based training, which was defined as: "*Team-based and individual physical activities under the control or guidance of the team's coaching or fitness staff that are aimed at maintaining or improving players' rugby skills or physical condition*". (Fuller *et al.*, 2007b). Match play was defined as: "*the total time a player was involved in match play, from either kick-off or from the moment the player was substituted onto the field, until the player was either substituted off the field, or the referee blew for full-time, excluding the half-time break".*

Prior to each pitch-based training session or competitive match, players were fitted with a GPS device (Optimeye S5, Catapult Innovations, Victoria, Australia) housing IMU technology. All players from across the three professional teams within this study wore the same manufacturing devices for the 2018/19 season. For training sessions and competitive matches, each player wore a tightly fitted vest (Catapult Innovations, Victoria, Australia) which allowed the devices to be housed within a pouch on the upper thoracic spine, between the scapulae. Devices were assigned to specific players throughout the season to minimise intraunit variability. Devices were turned on outside until a satellite reception had been picked up for outdoor sessions. Thereafter, players were fitted with their assigned device, and began warming up. On completion of each pitch-based training session (all other modes of exercise beyond pitch-based training were not included in this study) or competitive match, team coaching staff downloaded and processed all GPS data. The training and/or match data was then exported into Microsoft Excel as a CTR using Catapults Openfield software. The GPS and IMU variables were then extracted for each team (Edinburgh Rugby, Glasgow Warriors and Scotland International) and configured within a central database. The same period number format was applied to the external load data (period 0s), as previously used in Chapter 3, Study 1 (See Figure 4B.1).

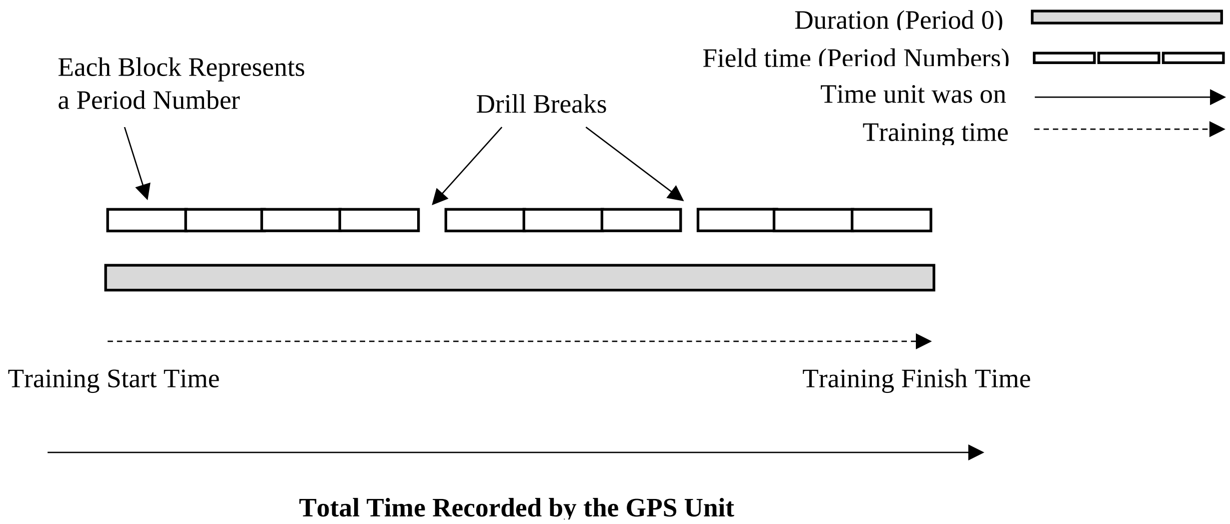


Figure 4B.1: Period zero values have been used in this study to track training and match external loads.

4B.2.4 Data Collection and Cleaning

The raw GPS data, which encompassed all external load variables used in this study (e.g., distance, PlayerLoad^{TM}, accelerations etc.) were taken from the same raw CTR exports used to collect all pitch-based training and match data for the 2018/19 season as previously outlined in Chapter 3, Study 1. The Chapter 3, Study 1 finalised database was filtered to only include 2018/19 data. All training and match raw data were collected and stored in separate databases. The data was then cross checked using the same aforementioned methods outlined in Chapter 3, Study 1 with each team's unique GPS database. This ensured all training sessions and competitive matches were accounted for over the 2018/19 season. Although the data was taken from the raw data files, team GPS databases were used if a session was missing or individual player data was missing from the raw data files. Where possible the raw data was cross-checked with each teams own GPS database to ensure accuracy. Occasionally certain variables had to be manually calculated. For example, if the HSR running data was missing from the period 0, then velocity band 4 and above was summed from the raw data so that that players HSR distance for that session could be inputted). Once both the individualised on-pitch training and match team databases for the 2018/19 season had been produced, a master database was created to encompass all training and match on-pitch data over the 2018/19 season. A final data check was conducted by cross checking all training sessions and matches with the on-pitch and match data collected in Chapter 3, Study 1 for the 2018/19 season.

4B.2.5 Exclusion Criteria and Estimated Data for External Load Variables

Data was collected from a total of 27 load-monitoring variables at the start of the study (see Table 4B.2). Prior to data analysis, set exclusion criteria for all of the indices of load were used to ensure data quality and accuracy. Data were excluded if:

1. Any external load variable required > 30% of the data to be estimated for one single team (Edinburgh Rugby, Glasgow Warriors and Scotland International separately).
2. Any external load variable resulted in > 20% of the data to be estimated when all team data was combined.
3. Any data across all variables that could not be accurately estimated from a training session or match was excluded
4. If the estimated data that was not possible to accurately estimate exceeded 20%, that variable was deemed unusable within the study

Table 4B.2: All possible external load variables and percentage of data needing estimated.

Variable	Edinburgh Rugby (%)	Glasgow Warriors (%)	Scotland International (%)	Combined Data (%)
Total Distance (m)	0.02	0.67	1.32	0.46
Running (> 2.0 m·s)	1.17	19.81	2.93	10.28
High Speed Running (> 5.0 m·s)	0.26	0.79	2.93	0.79
Sprint Metres (m)	0.06	19.81	2.93	9.82
Acceleration meters (> 2 $m \cdot s^{-2}$)	0.05	1.27	2.93	0.92
Acceleration meters (> 3 $m \cdot s^{-2}$)	0.13	1.27	2.93	0.96
Deceleration meters (< 2 $m \cdot s^{-2}$)	1.14	28.79	2.93	14.58
Maximum Acceleration ($m \cdot s^{-2}$)	10.96	**67.56***	4.84	**37.47***
Maximum Deceleration ($m \cdot s^{-2}$)	4.72	**67.57***	4.59	**34.83***
Meters per Minute	**56.58***	20.01	2.93	**33.62***
Scrum Count (n)	**78.99***	**85.78***	2.93	**74.55***
Average Scrum Duration (s)	**78.99***	**85.78***	2.93	**74.55***
Total Acceleration Load	26.57	28.47	4.06	**25.21***
Acceleration Density	**57.66***	**99.95***	4.06	**72.50***
PlayerLoad™ (AU)	0.06	28.29	2.93	13.88
PlayerLoad Slow (accelerations < 2m/s)	1.38	28.45	2.93	14.51
Acceleration Efforts >90% Maximum (n)	**64.97***	28.32	5.77	**41.41***
PlayerLoad™ Efforts >80% Maximum (n)	**66.89***	28.32	4.01	**42.04***
Metres > 60% Maximum Velocity (m)	16.74	1.80	4.01	8.29
Metres > 80% Maximum Velocity (m)	16.74	0.78	4.01	7.80
Metres > 90% Maximum Velocity (m)	16.74	0.78	4.01	7.80
Acceleration Efforts > 2 $m \cdot s^{-2}$ (n)	25.14	19.76	2.93	20
Acceleration Efforts > 3 $m \cdot s^{-2}$ (n)	25.15	19.83	2.93	20
Deceleration Efforts < 2 $m \cdot s^{-2}$ (n)	26.35	**100.00***	**100.00***	**69.10***

NOTE: Bold data with an asterisk (*) signifies data needing estimated > 30% for each team and > 20% for the combined total.

For data to be deemed accurately estimated (and thus included in the study), the following conditions had to be met:

1. Player on-pitch training data must be estimated by a player who played in the same position (Forward or Back), or, in every incidence possible, from the same positional group (Prop, Hooker, Second Row, Back Row, Scrum Half, Stand Off, Centre, Back 3), for the same training session.
2. Player match data must be estimated from a player playing within the same positional group (Prop, Hooker, Second Row, Back Row, Scrum Half, Stand Off, Centre, Back 3), who played no longer or shorter than 10 minutes of the player who's data had to be estimated.

If the following conditions were not met, the data was excluded from the study, as it was deemed to be beyond the boundaries of accurate estimation. Based on this exclusion criteria, a further 3 variables were excluded from the study (See Table 4B.3).

Table 4B.3: Percentage of data excluded based on inaccurate estimations.

Variable	Edinburgh Rugby	Glasgow Warriors	Scotland International	Total
Total Distance (m)	0.00	0.00	1.22	0.12
Running (>2.0 m·s)	0.86	18.64	2.30	9.50
High Speed Running (>5.0 m·s)	0.00	0.00	2.30	0.23
Sprint Metres (m)	0.00	18.65	2.30	9.14
Acceleration meters (> 2 $m{\cdot}s^{-2}$)	0.00	0.00	2.30	0.23
Acceleration meters (> 3 $m{\cdot}s^{-2}$)	0.00	0.00	2.30	0.23
Deceleration meters (< 2 $m{\cdot}s^{-2}$)	0.86	**20.01***	2.30	10.15
PlayerLoad™ (AU)	0.00	19.66	2.30	9.62
PlayerLoad Slow (accelerations < 2 $m{\cdot}s^{-2}$)	0.00	19.66	2.30	9.62
Metres > 60% Maximum Velocity (m)	16.42	0.51	3.37	7.50
Metres > 80% Maximum Velocity (m)	16.42	0.00	3.37	7.25
Metres > 90% Maximum Velocity (m)	16.42	0.00	3.37	7.25
Acceleration Efforts > 2 $m{\cdot}s^{-2}$ (n)	**23.91***	18.70	2.30	19.23
Acceleration Efforts > 3 $m{\cdot}s^{-2}$ (n)	**23.91***	18.76	2.30	19.26

NOTE: Bold data with an asterisk (*) signifies data exclusion > 20% for that particular variable.

Following the exclusion of deceleration meters (< 2 $m{\cdot}s^{-2}$), acceleration efforts > 2 $m{\cdot}s^{-2}$ and acceleration efforts > 3 $m{\cdot}s^{-2}$, a further 3 variables were excluded from the study. Firstly, running meters were excluded, as TD and HSR are often included in workload studies, and have shown associations with injury risk in multiple team sports (Blanch & Gabbett, 2016; Hulin *et al.*, 2016b; Weaving *et al.*, 2018). Therefore, running meters > 2.0 m·s was concluded to be an extra, but unnecessary variable. Secondly, Sprint distance > 7.5 m/s was also excluded. This was because 80 and 90% of maximum velocity were considered to be more individualised measures of high-speed locomotive activity, and previous literature has shown individualised measures of running load to provide additional load information in Rugby Union (Weaving *et al.*, 2018). Lastly, meters > 90% maximum velocity was excluded due to a lack of data (players did not achieve meters > 90% maximum velocity often, meaning there were a large number of weeks with 0s). This has large repercussions on the load monitoring calculations, particularly for the ACWR. A final point is that total distance was included as a two season analysis separately. This was because there was an entire season's worth of data for this load monitoring variable that was not available for any other metric.

4B.2.6 Bivariate Correlations and Variance Inflation Factors

Bivariate correlations and variance inflation factors were conducted on SPSS to check for potential multi-collinearity for the remaining variables. There was a large correlation between PlayerLoad™ and PlayerLoad Slow, as well as acceleration meters > 2 $m \cdot s^{-2}$ and acceleration meters > 3 $m \cdot s^{-2}$, and HSR meters and meters > 60% maximum velocity (see Table 4B.4).

Table 4B.4: Bivariate correlations between remaining variables.

	HSR	Acc > 2	Acc > 3	PlayerLoad™	PLSlow	Meters > 60%	Meters > 80%
HSR	1	.667**	.506**	.476**	.212**	**.801****	.395**
Acc > 2	.667**	1	**.806****	.639**	.444**	.552**	.214**
Acc > 3	.506**	**.806****	1	.358**	.228**	.400**	.178**
PlayerLoad™	.476**	.639**	.358**	1	**.896****	.431**	.186**
PLSlow	.212**	.444**	.228**	**.896****	1	.223**	.110**
Meters > 60%	**.801****	.552**	.400**	.431**	.223**	1	.517**
Meters > 80%	.395**	.214**	.178**	.186**	.110**	.517**	1

NOTE: Bold data with an asterisk (*) signifies bivariate correlation > 0.70.

Assessment of the VIFs reported that there was multicollinearity for PlayerLoad™, which, given the correlation between PlayerLoad™ and PlayerLoad Slow, meant that one of these variables would need to be excluded from the study (see Table 4B.5). Given the multiple studies that have used PlayerLoad™ as an overall metric for training and/or match load (Howe *et al.*, 2017; Weaving *et al.*, 2018; Cummins *et al.*, 2019), the researcher decided that this was the more appropriate measure to include within the study.

Table 4B.5: Original variance inflation factor (VIF) values.

Collinearity Statistics	
Workload Variables	**VIF**
High Speed Running (> 5.0 m·s)	3.964
Acceleration meters (> 2 $m·s^{-2}$)	5.809
Acceleration meters (> 3 $m·s^{-2}$)	3.314
PlayerLoad™ (AU)	**10.644***
PlayerLoad Slow (accelerations < 2m/s)	7.503
Metres > 60% Maximum Velocity (m)	3.270
Metres > 80% Maximum Velocity (m)	1.393

NOTE: Bold data with an asterisk (*) signifies VIF > 10

The VIFs for all remaining workload variables were < 10 (see Table 4B.6). Data analysis was thus carried out on: TD (independent two-season analysis); HSR Distance (meters covered > 5.0 m.s); Relative Distance Metres (distance > 60 and 80% of maximum velocity); Acceleration Distance (meters > 2 $m·s^{-2}$ and meters > 3 $m·s^{-2}$) and PlayerLoad™ (see Table 4B.7 for the description and calculation of each workload variable).

Table 4B.6. Final variance inflation factor (VIF) values.

Collinearity Statistics	
Workload Variables	**VIF**
High Speed Running (> 5.0 m·s)	3.503
Acceleration meters (> 2 $m·s^{-2}$)	5.637
Acceleration meters (> 3 $m·s^{-2}$)	3.255
PlayerLoad™ (AU)	1.935
Metres > 60% Maximum Velocity (m)	3.269
Metres > 80% Maximum Velocity (m)	1.387

Table 4B.7: The training and match variables assessed.

Load Monitoring Variables	Description	Calculation
Total Distance	The total distance a player covered from the start to the end of the training session or match	Calculated by summing the distance a player had covered in meters for each training session (see chapter 4b, section 4.5.4). For game days, the total distance was taken as the distance in meters the player covered while on the field competing in match play.
High-Speed Running Distance	The distance a player covered from the start to the end of the training session or match above 5.0 m·s.	Calculated by summing the distance in meters a player had covered in each training session (or the distance covered during match play) above 5.0 m·s.
Relative Distance > 60 % of Max Velocity	The distance a player covered from the start to the end of the training session or match above that was above 60% of their maximum velocity	Calculated by summing the distance a player had covered in meters above 60% of their maximum velocity for each training session or match.
Relative Distance > 80% of Max Velocity	The distance a player covered from the start to the end of the training session or match above that was above 80% of their maximum velocity	Calculated by summing the distance a player had covered in meters above 80% of their maximum velocity for each training session or match.
Acceleration Distance (> 2 $m{\cdot}s^{-2}$)	The distance a player covered while accelerating above 2 $m{\cdot}s^{-2}$ during a training session or match	Calculated by summing the distance a player covered in meters while accelerating above 2 $m{\cdot}s^{-2}$ during for all training sessions complete in a day, or while the player was on the field competing in match play.
Acceleration Distance (> 3 $m{\cdot}s^{-2}$)	The distance a player covered while accelerating above 3 $m{\cdot}s^{-2}$ during a training session or match	Calculated by summing the distance a player covered in meters while accelerating above 3 $m{\cdot}s^{-2}$ during for all training sessions complete in a day, or while the player was on the field competing in match play.
PlayerLoad™	Instantaneous rate of change of acceleration (divided by a scaling factor) measured in each of the three planes (vertical, medial-lateral and anterior-posterior). Therefore giving a total workload value from summation of movement in the 3 axis. It is presented as an arbitrary unit (AU).	Calculated by summing the PlayerLoad™ score for all training sessions complete in a day, or while the player was on the field competing in match play.

4B.2.7 The Recording of Injury Data and Injury Definitions

As per Chapter 3, player injury data was collected for all players involved in this study across the three professional teams. Qualified team medical personnel collected data via Microsoft Excel (Version 16), and recorded injury data via the Orchard Sports Injury Classification System (Version 10) (Rae and Orchard, 2007).

As per Chapter 3, injuries were recorded according to the World Rugby Consensus Group. All injury definitions were kept the same. As such, an injury was defined as "*Any physical complaint, which was caused by a transfer of energy that exceeded the body's ability to maintain its structural and/or functional integrity, that was sustained by a player during a rugby match or rugby training*." (Fuller *et al.*, 2007b, p. 329). Similarly, injuries were recorded using a fully inclusive time loss definition ("*any injury that prevents a player from taking a full part in all training activities typically planned for that day and/or match play for more than 24 hours from midnight at the end of the day the injury was sustained*") (Brooks *et al.*, 2008, p. 864).

4B.2.8 Data Analyses

Weekly data was categorised from Monday to Sunday. For each load monitoring variable, weekly load, as well as 2-, 3- and 4-week cumulative loads were calculated. In addition to cumulative load, weekly change in load and uncoupled ACWRs via 1:4 weekly time points were calculated (see Table 4B.8). Given a common finding recently presented in workload-injury studies, chronic workloads were split from the median score for each variable and separated into high and low categories (Andrade *et al.*, 2020). This allowed the influence of high and low chronic loading in relation to the ACWR to be analysed for injury risk association (See Table 4B.9 for team chronic splits and Supplementary Table 14 in Appendix F for positional group chronic splits).

Table 4B.8: Derived training variables from each load-monitoring variable.

Training Exposure Variables	Description	Calculation
Daily load	Total training load for all sessions completed in one day	All sessions were summed for each day (e.g., if a player completed two pitch-based training sessions at 2000 m and 1500m, their daily load for total distance would be 3500 m)
Weekly load	The total load a player was subjected to over a weekly period (including match load)	Calculated by summing a player's daily load from the previous 7 days (week commencing on a Monday)
Week-to-week change in load	Absolute difference between the current week's total load and the previous week's total load (including match load).	Sum of the current week's load is subtracted from the sum of the previous week's load.
1-, 2-, 3- and 4-week cumulative loads	Sum of total training load for the previous 7, 14, 21 and 28 days (including match loads)	1, 2, 3, and 4-week rolling loads accumulated over 7, 14, 21 and 28 days.
Acute: chronic workload ratio (rolling uncoupled)	A player's most recent 1-week load (acute workload) and their previous 3-week uncoupled rolling average (chronic workload) is expressed as a ratio to inform injury risk.	Acute (uncoupled rolling 7-day) workload is divided by chronic (previous 21-day uncoupled rolling) workload.
Chronic Workload Status	A player was considered to be in a high chronic loading state if they were equal to or above the median split based on the chronic part of the ACWR calculation. A player was considered to be in a low chronic loading state if they were below the median split based on the chronic part of the ACWR calculation.	Calculated by taking the median score for the chronic load calculation

Table 4B.9: Workload median splits for low and high chronic states for each external load variable. Players in a low chronic workload state were below the median value and players in a high chronic loading state were equal to or above the median value.

Workload Variable	Team Analysis
TD	13477
HSR	1147
Acc > 2	526
Acc > 3	69
PlayerLoadTM	1307
Meters > 60%	700
Meters > 80%	53

NOTE: TD, total distance; HSR, high-speed running distance; acc > 2, acceleration meters above 2 $m \cdot s^{-2}$; acc > 3, acceleration meters above 3 $m \cdot s^{-2}$; meters > 60%, meters covered above 60% of maximum velocity; meters > 80%, meters covered above 80% of maximum velocity.

Workload was classified into very low through to very high discrete ranges via equal frequency sextiles (See Table 4B.10 and 4B.11). Subsequent injury (7-day) data was analysed in relation to workloads for each variable. Non-training weeks and RTP sessions were included in cumulative, weekly change and ACWR data given the potential impact of returning to full-training following an injury or time off. The calculations for each variable started on that player's first week of training, rather than the first week of the season (i.e., if a player completed their first week of training in week 8, then the calculations started on week 8, and ran until the player's last week of training). Prior to conducting the statistical analysis, non-training weeks were removed once the formulas for each derived load monitoring measure had been converted to values only in Microsoft Excel. This was because non-training weeks cannot result in an on-pitch or match injury (i.e., if the player was not training or competing in competitive matches, the player could not be injured). This prevented very low ACWRs, and very low chronic loads being skewed toward reduced injury. See Supplementary Tables 2 – 11 for positional group analysis in Appendix F.

4B.2.9 Workload Categories

Table 4B.10: The classifications and boundaries for each workload classification over 1-4 accumulated weeks and the absolute change from week-to-week.

		No. of Weeks Accumulated				
	Classification	1	2	3	4	Weekly Change
TD (m)	Very low	< 8129	< 17,271	<26,288	< 34,813	< 1486
	Low	8129 - 11,545	17,271 - 23,156	26,288 - 34,573	34,813 - 45,912	1486 - 3,083
	Intermediate low	11,546 - 14,230	23,157 - 27,480	34,574 - 40,757	45,913 - 53,724	3,084 - 4,814
	Intermediate high	14,231 - 16,974	27,481 - 32,092	40,759 - 46,716	53,725 - 61,406	4,815 - 7,127
	High	16,975 - 20,611	32,093 - 38,243	46,717 - 55,053	61,407 - 71,503	7,128 - 10,760
	Very high	> 20,611	> 38,245	> 55,053	>71,503	>10,760
HSR (m)	Very low	< 520	< 1130	< 1697	< 2253	< 162
	Low	520 - 887	1130 - 1793	1698 - 2703	2253 - 3501	162 - 323
	Intermediate low	888 - 1268	1794 - 2529	2704 - 3677	3502 - 4830	324 - 531
	Intermediate high	1269 - 1738	2530 - 3388	3678 - 4957	4831 - 6536	532 - 823
	High	1739 - 2363	3389 - 4488	4958 - 6427	6537 - 8335	824 - 1315
	Very high	> 2363	> 4488	> 6427	> 8335	> 1315
Accelerations (> 2 m·s^{-2})	Very low	< 306	< 649	< 990	< 1292	< 65
	Low	306 - 450	649 - 903	990 - 1339	1292 - 1797	65 - 140
	Intermediate low	451 - 572	904 - 1128	1340 - 1663	1798 - 2175	141 - 227
	Intermediate high	753 - 709	1129 - 1366	1664 - 2000	2176 - 2629	228 - 333
	High	710 - 915	1367 - 1701	2001 - 2454	2630 - 3224	334 - 499
	Very high	> 915	> 1701	> 2454	> 3224	> 499
Accelerations (> 3 m·s^{-2})	Very low	< 26.2	< 61	< 95	< 128	< 11
	Low	26.2 - 47.6	61 - 102	95 - 159	128 - 212	11 - 23
	Intermediate low	47.7 - 72.3	103 -149	160 - 220	213 - 292	23 - 39
	Intermediate high	72.3 - 101.1	150 - 201	221 - 295	293 - 389	40 - 62
	High	101.2 - 150.4	202 - 278	296 - 402	390 - 522	63 - 101
	Very high	> 150.4	> 278	> 402	> 522	> 101
PlayerLoad™	Very low	< 782.2	< 1704	< 2603	< 3399	< 164
	Low	782.2 - 1163.2	1704 - 2308	2603 - 3463	3399 - 4607	164 - 326
	Intermediate low	1163.3 - 1444.3	2309 - 2768	3464 - 4090	4608 - 5383	327 - 517
	Intermediate high	1444.4 - 1730.2	2769 - 3223	4091 - 4733	5384 - 6174	518 - 770
	High	1730.3 - 2098.2	3224 - 3860	4734 - 5510	6175 - 7156	771 - 1140
	Very high	> 2098.2	> 3860	> 5510	> 7156	> 1140
Metres > 60% max (m)	Very low	> 250	< 600	< 971	< 1294	< 98
	Low	250 - 534	600 - 1101	971 - 1692	1294 - 2226	98 -223
	Intermediate low	535 - 769	1102 - 1529	1693 - 2262	2227 - 2975	224 - 372
	Intermediate high	770 - 1044	1530 - 2008	2264 - 2925	2976 - 3816	373 - 586
	High	1045 - 1427	2009 - 2659	2926 - 3811	3817 - 4931	587 - 918
	Very high	> 1427	> 2659	>3811	> 4931	> 918
Metres > 80% max (m)	Very low	0	< 17	< 36	< 59	< 5
	Low	0.4 - 22.7	17 - 65	36 - 111	59 - 156	5 - 21
	Intermediate low	22.8 - 50	66 -116	112 - 185	157 - 256	22 - 44
	Intermediate high	50.1 - 90.8	117 - 192	186 - 292	257 - 400	45 - 81
	High	90.9 - 170.3	193 - 335	293 - 504	401 - 692	82 - 156
	Very high	> 170.3	> 335	> 504	> 692	157 - 2700

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Table 4B.11: Classifications and boundaries for: (ACWR) acute: chronic workload ratios overall, (low chronic) acute: chronic workload ratios combined with low chronic workload and (high chronic) acute: chronic workload ratios combined with high chronic workloads.

	Classification	ACWR	Low Chronic	High Chronic
TD (m)	Very low	< 0.62	< 0.77	< 0.56
	Low	0.63 - 0.89	0.77 - 1.02	0.56 - 0.77
	Intermediate low	0.90 - 1.06	1.03 - 1.29	0.78 - 0.95
	Intermediate high	1.07 - 1.29	1.30 - 1.56	0.96 - 1.09
	High	1.30 - 1.64	1.57 - 2.04	1.10 - 1.29
	Very high	> 1.64	> 2.04	> 1.29
HSR (m)	Very low	< 0.54	< 0.52	< 0.55
	Low	0.54 - 0.79	0.52 - 0.88	0.55 - 0.75
	Intermediate low	0.80 - 1.00	0.89 - 1.12	0.76 - 0.96
	Intermediate high	1.01 -1.28	1.13 - 1.56	0.97 - 1.13
	High	1.29 - 1.77	1.57 - 2.45	1.14 - 1.43
	Very high	> 1.77	> 2.45	> 1.43
Accelerations (> 2 m·s^{-2})	Very low	< 0.60	< 0.74	< 0.56
	Low	0.60 - 0.86	0.74 - 1.00	0.56 - 0.76
	Intermediate low	0.87 - 1.04	1.01 - 1.29	0.77 - 0.93
	Intermediate high	1.05 - 1.30	1.30 - 1.65	0.94 - 1.11
	High	1.31 - 1.74	1.66 - 2.31	1.12 - 1.35
	Very high	> 1.74	> 2.31	> 1.35
Accelerations (> 3 m·s^{-2})	Very low	< 0.42	< 0.48	<0.41
	Low	0.42 - 0.72	0.48 - 0.90	0.41 - 0.63
	Intermediate low	0.73 - 1.00	0.91 - 1.23	0.64 - 0.86
	Intermediate high	1.01 - 1.35	1.24 - 1.78	0.87 - 1.12
	High	1.36 - 2.05	1.79 - 3.01	1.13 - 1.53
	Very high	> 2.05	>3.01	> 1.53
PlayerLoad™	Very low	< 0.61	< 0.73	< 0.56
	Low	0.61 - 0.88	0.74 - 1.03	0.56 - 0.77
	Intermediate low	0.89 - 1.08	1.04 - 1.33	0.78 - 0.95
	Intermediate high	1.09 - 1.33	1.34 - 1.64	0.96 - 1.13
	High	1.34 - 1.68	1.65 - 2.21	1.14 - 1.35
	Very high	> 1.68	> 2.21	> 1.35
Metres > 60% max (m)	Very low	< 0.39	< 0.15	< 0.49
	Low	0.39 - 0.72	0.15 - 0.78	0.49 - 0.70
	Intermediate low	0.73 - 0.99	0.79 - 1.17	0.71 - 0.90
	Intermediate high	1.00 - 1.29	1.18 - 1.72	0.91 - 1.11
	High	1.30 - 1.90	1.73 - 2.92	1.12 - 1.43
	Very high	> 1.90	> 2.92	> 1.43
Metres > 80% max (m)	Very low	0		< 0.13
	Low	0.01 - 0.24	0	0.13 - 0.36
	Intermediate low	0.25 - 0.62	0.01 - 0.64	0.37 - 0.62
	Intermediate high	0.63 - 1.14	0.65 - 1.70	0.63 - 0.99
	High	1.15 - 2.44	1.71 - 4.38	1.00 - 1.61
	Very high	> 2.44	> 4.38	> 1.61

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

4B.2.10 Statistical Analyses

Injury incidence was calculated as injuries per 1000 hours of "on-legs" training or match play exposure (i.e., total number of injuries divided by training or match hours, and presented in injuries per 1000 hours). Injury risk was calculated as the number of injuries sustained relative to the number of individual training or match exposures for each workload classification. For each load-monitoring calculation (cumulative loads, weekly change and the ACWR), the workload variables were splint into sextiles (very low, low, intermediate-low, intermediate-high, high and very high), and the lowest range group (very low) was used as a reference group. Binary logistic regression was used to investigate all workload variables independently in relation to injured vs. non-injured players for subsequent week injuries. Load-monitoring calculations were modelled as predictor variables, and injury vs. no injury as the dependent variable. Odds ratios (OR) were calculated to determine the injury risk of each workload metric. When an OR was greater than 1.00, an increased risk of injury in the subsequent week was reported (e.g., OR=1.50 is indicative of a 50% increased risk; OR=0.50 is indicative of a 50% reduction in injury risk). Correlation coefficients between workload measures, alongside Variance Inflation Factors (VIF), were used to detect multicollinearity between workload variables. If the VIF was ≥10, then substantial multicollinearity was shown. Data were analysed using IBM SPSS Statistics V.26.0 (IBM Corporation, New York, USA). Data is reported as means ± standard deviation (SD) unless specified as 95% confidence intervals. Given the short timeframe in which data was collected, significance was accepted at $p < 0.01$ to reduce type 1 error rate.

4B.3 RESULTS

4B.3.1 Injury Incidence

4B.3.1.1 One Season Analysis

Players sustained 408 injuries over the 2018/19 season (18.2 injuries per 1000 hours of "on-legs" exposure). A total of 152 injuries were a result of on-pitch training (7.3 injuries per 1000 hours of "on-legs" exposure), whereas 256 were a result of match play. Match play resulted in an incidence rate over twenty times greater than that of training (158.5 injuries per 1000 hours of "on-legs" exposure). A total of 7854 days were lost due to injury over the season (training = 2664 days, match = 5190 days).

4B.3.1.2 Two Season Analysis

Players sustained 687 injuries over the 2017/18 and 2018/19 seasons (15.2 injuries per 1000 hours of "on-legs" exposure). A total of 258 injuries were a result of on-pitch training (6.2 injuries per 1000 hours of "on-legs" exposure), and 429 were due to match play. Over the two seasons, match play also resulted in an incidence rate over twenty times greater than that of training (131.4 injuries per 1000 hours of "on-legs" exposure). A total of 14,353 days were lost due to on-pitch related injuries over the two seasons (training = 5323 days, match = 9212 days).

4B.3.2 Cumulative Loads and Weekly Change

A low weekly change for acceleration meters > 2 $m \cdot s^{-2}$ (65 – 140m) had a significantly lower injury risk compared to the reference category (OR = 0.59, 95% CIs = 0.41 – 0.84, $p < 0.01$). In addition, a high weekly change in acceleration meters > 2 $m \cdot s^{-2}$ (334 – 499m) (OR = 0.60, 95% CIs = 0.42 – 0.86, $p < 0.01$) also significantly reduced injury risk (see Table 4B.12). Over 1-weekly periods, the odds of injury for players with very high PlayerLoad™ (> 2098.2AU) were higher than the reference group (OR = 2.3, 95% CIs = 1.11 – 4.89, $p < 0.05$), but this was not significant. Players with very high TD (> 20,611m), HSR (> 2363m), very high acceleration meters > 2 $m \cdot s^{-2}$ (> 915m) and very high acceleration meters > 3 $m \cdot s^{-2}$ (> 150.4m) had the greatest odds of injury compared to all other categories for 1-weekly loads, but these were not significant. Over 2-weekly cumulative periods, players with higher meters > 80% maximum compared to the reference group were more likely to be injured but these were also not significant (intermediate low workload [904 – 1128m] OR = 2.14, 95% CIs = 1.05 – 4.4 , $p < 0.05$; high workload [2001 – 2545m] OR = 2.47, 95% CIs = 1.08 – 5.64, $p < 0.05$; very high workload [> 2454m] OR = 2.61, 95% CIs = 1.03 – 6.55, $p < 0.05$). All workload groups for meters > 60% of maximum velocity had a higher injury risk compared to the reference category for 3-week periods, but these were not significant. No workload groups across any variable were significantly associated with injury for 4-week cumulative loads. Higher weekly changes for TD reported an increased odds of injury for intermediate high (7128 – 10,760m) (OR = 1.35, 95% CIs = 1.02 – 1.79, $p < 0.05$) and very high (> 10,760m) weekly changes (OR = 1.37, 95% CIs = 1.01 – 1.86, $p < 0.05$), but these were not significant.

4B.3.3 The Acute: Chronic Workload Ratio and Chronic Loading

When all chronic loads were combined, an intermediate high ACWR for acceleration meters > 2 $m \cdot s^{-2}$ (1.05 – 1.30) (OR = 0.46, 95% CIs = 0.28 – 0.75, $p < 0.01$) significantly reduced injury risk. All other ACWRs across each workload variable were not significant when all chronic loads were combined (see Table 4B.13). When in a low chronic workload state, a low ACWR for HSR (0.52 – 0.88) significantly reduced the odds of injury compared to the reference category (OR = 0.48, 95% CIs = 0.27 – 0.84, $p = 0.01$). High chronic workloads combined with a low ACWR for TD (0.56 – 0.77) and acceleration meters > 2 $m \cdot s^{-2}$ (0.56 – 0.76) reduced injury risk (OR = 0.62, 95% CIs = 0.42 – 0.92, $p < 0.05$; OR = 0.53, 95% CIs = 0.33 – 0.88, $p < 0.05$, respectively), but these were not significant.

Table 4B.12: Injury risk (reported via odds ratios) associated with accumulated workloads and week-to-week change in workloads for all players.

	Classification	1 Weekly	2 Weekly	3 Weekly	4 Weekly	Weekly Change
TD (m)	Very low	/	/	/	/	/
	Low	1.09	0.94	1.44	1.25	1.05
	Intermediate low	1.21	0.83	1.23	1.51	1.02
	Intermediate high	1.33	1.06	1.54	1.31	1.35
	High	1.22	1.27	1.34	1.25	1.30
	Very high	1.50	1.34	1.33	1.28	1.37
HSR (m)	Very low	/	/	/	/	/
	Low	0.76	1.22	0.87	1.12	0.99
	Intermediate low	1.16	1.02	1.18	0.96	1.10
	Intermediate high	1.02	1.07	1.06	1.00	0.90
	High	0.89	1.44	1.11	0.95	0.76
	Very high	1.16	1.42	0.72	1.42	0.72
Accelerations ($> 2\ m \cdot s^{-2}$)	Very low	/	/	/	/	/
	Low	0.75	1.26	1.29	0.87	**0.59***
	Intermediate low	1.10	1.14	1.01	1.14	0.79
	Intermediate high	1.24	0.98	1.23	1.35	0.70
	High	1.09	1.14	1.32	0.80	**0.60***
	Very high	1.35	0.89	1.50	1.24	0.67
Accelerations ($> 3\ m \cdot s^{-2}$)	Very low	/	/	/	/	/
	Low	0.97	1.00	1.27	0.91	1.32
	Intermediate low	1.08	1.04	1.31	0.74	1.03
	Intermediate high	1.07	1.23	1.06	0.93	1.20
	High	1.09	1.52	0.95	0.94	0.96
	Very high	1.39	1.19	0.90	0.98	1.14
PlayerLoad™	Very low	/	/	/	/	/
	Low	1.38	0.87	0.96	1.13	0.93
	Intermediate low	1.15	0.75	1.36	1.12	1.11
	Intermediate high	1.46	0.78	1.36	1.21	0.90
	High	1.32	1.05	1.48	0.66	1.07
	Very high	2.33	0.81	0.78	1.40	0.87
Metres > 60% max (m)	Very low	/	/	/	/	/
	Low	0.85	0.58	1.33	0.93	1.19
	Intermediate low	1.49	0.79	2.29	1.06	0.99
	Intermediate high	1.30	0.60	1.35	1.42	1.48
	High	1.07	0.90	1.36	1.39	1.22
	Very high	0.95	0.63	1.30	2.17	0.75
Metres > 80% max (m)	Very low	/	/	/	/	/
	Low	0.70	1.77	1.12	0.68	0.76
	Intermediate low	0.61	2.14	1.33	0.58	0.84
	Intermediate high	1.05	1.87	1.29	0.56	0.84
	High	1.37	2.47	1.40	0.52	0.64
	Very high	1.09	2.60	0.84	0.57	0.90

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Accelerations ($> 2\ m \cdot s^{-2}$), acceleration meters $> 2\ m \cdot s^{-2}$; Accelerations ($> 3\ m \cdot s^{-2}$), acceleration meters $> 3\ m \cdot s^{-2}$; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity; * $p < 0.01$. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Table 4B.13: Injury risk associated with: (ACWR) acute: chronic workload ratios overall, (low chronic) acute: chronic workload ratios combined with low chronic workload and (high chronic) acute: chronic workload ratios combined with high chronic workloads for all players.

	Classification	Uncoupled ACWR	Low Chronic	High Chronic
TD (m)	Very low	/	/	/
	Low	0.65	0.80	0.62
	Intermediate low	0.83	1.36	0.88
	Intermediate high	0.90	1.03	0.76
	High	0.74	1.15	1.08
	Very high	0.69	0.88	1.26
HSR (m)	Very low	/	/	/
	Low	0.65	**0.48***	1.01
	Intermediate low	0.64	0.80	1.10
	Intermediate high	0.70	1.05	1.05
	High	0.80	0.83	1.10
	Very high	0.81	0.67	1.28
Accelerations (> 2 m·s^{-2})	Very low	/	/	/
	Low	0.65	0.80	0.54
	Intermediate low	0.69	0.62	0.89
	Intermediate high	**0.46***	0.98	0.84
	High	0.72	1.39	0.68
	Very high	0.78	0.83	0.94
Accelerations (> 3 m·s^{-2})	Very low	/	/	/
	Low	0.83	0.50	1.03
	Intermediate low	0.62	0.92	0.68
	Intermediate high	0.72	0.69	0.83
	High	0.81	0.98	0.83
	Very high	0.68	0.84	1.20
PlayerLoad™	Very low			
	Low	0.68	1.12	0.78
	Intermediate low	0.80	1.01	0.98
	Intermediate high	0.75	1.34	0.87
	High	0.57	1.58	1.03
	Very high	0.60	0.92	0.72
Metres > 60% max (m)	Very low	/	/	/
	Low	0.75	0.73	1.23
	Intermediate low	0.55	0.83	1.00
	Intermediate high	0.82	1.36	0.89
	High	0.90	1.93	1.22
	Very high	1.13	0.96	1.06
Metres > 80% max (m)	Very low	/		/
	Low	1.80	/	1.31
	Intermediate low	1.61	1.32	1.55
	Intermediate high	0.98	0.61	1.49
	High	1.03	1.17	1.11
	Very high	0.76	1.22	1.09

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Accelerations (> 2 m·s^{-2}), acceleration meters > 2 m·s^{-2}; Accelerations (> 3 m·s^{-2}), acceleration meters > 3 m·s^{-2}; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity; * $p < 0.01$. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

4B.4 DISCUSSION

4B.4.1 Main Findings

There is a lack of research in Rugby Union compared to other team sports for determining which training and match workload variables are most useful for monitoring and understanding the risk of injury. Therefore, this study aimed to investigate a number of GPS and IMU derived workloads that are used to track the demands of training and match play in professional Rugby Union, and their relationship to injury risk. In order to achieve this aim, a number of commonly used workload measures that are used in professional team sports settings were included. These were: 1 – 4 weekly cumulative timeframes, weekly changes in load and the ACWR (including the ACWR at a low and high chronic workload status). The analysis was carried out to investigate the overall implication of GPS/IMU workload on injury risk for all professional Rugby Union players. There was a lack of significant findings in the present study, however there are potential avenues in which future research may wish to explore based on the current findings.

A low and high weekly change for acceleration meters > 2 $m \cdot s^{-2}$ (65 – 140m and 334 – 499m, respectively) significantly reduced injury risk in the present study, whereas all other findings were not significantly associated with an increase or decrease in injury risk compared to their respective reference categories. Nevertheless, there are areas highlighted in the present study that may be worth investigating with more data (i.e., more teams and/or seasons worth of data). Over 1-weekly periods, very high 1-weekly PlayerLoad^{TM} (> 2098.2AU) was associated with an increased injury risk. Furthermore, over 2-weekly cumulative periods, intermediate low (904 – 1128m), high (2001 – 2545m) and very high (> 2454m) meters > 80% maximum velocity was associated with an increased injury risk, although not significant ($p < 0.05$). An intermediate high and very high weekly change in TD (4,815 – 7,127m and > 10,760m, respectively) significantly increased injury risk compared to the reference group also.

An intermediate high ACWR for acceleration meters > 2 $m \cdot s^{-2}$ (1.05 – 1.30) (OR = 0.46, 95% CIs = 0.28 – 0.75, $p < 0.01$) significantly reduced injury risk when all chronic loads were combined. Furthermore, a low ACWR for HSR (0.52 – 0.88) significantly reduced the odds of injury compared to the reference category when in a low chronic workload state (OR = 0.48, 95% CIs = 0.27 – 0.84, $p = 0.01$).

4B.4.2 Cumulative Loads and Weekly Change

In the present study, professional Rugby Union players who had a very high PlayerLoad™ (> 2098AU) over 1-weekly periods had a higher injury risk compared to the reference group (< 782AU). Although not significant, there was a trend in the current study for very high loads over 1-weekly periods elicited the greatest odds of injury compared to all other workload groups for a number of workload variables. This was reported for TD (> 20,611m), HSR distance (> 2363m), acceleration meters > 2 $m \cdot s^{-2}$ (> 915m) and acceleration meters > 3 $m \cdot s^{-2}$ (> 150.4m). Similar findings have been reported in a number of other team sports. For instance, Murray *et al.* (2017c), reported that elite Australian Football players with a PlayerLoad™ >2500AU over 1-weekly periods were significantly more likely to be injured than the reference group. In addition, Jaspers *et al.* (2018), reported a likely harmful effect for a high 1-weekly TD (>31, 161m) in professional Soccer players, whereas Bowen *et al.* (2017), reported low 1-weekly TD significantly reduced injury risk in elite soccer players. Beyond just GPS and IMU data, using the sRPE method, Malone *et al.* (2017c), reported that high 1-weekly workloads (> 2770 AU) were associated with a significantly higher risk of injury compared to a reference (low workload) group in elite Gaelic Football players. Although taken from a multitude of team sports - which truthfully may not necessarily reflect the demands of Rugby Union - these findings collectively suggest that player injury risk may be heightened if the workloads over acute periods are excessive, in a multitude of team-sporting environments.

Indeed, acute vigorous workloads may reduce the stress-bearing capacity of the musculoskeletal tissue, thereby increasing the likelihood of failure of the adaptive mechanisms to withstand the high force loads, and consequently resulting in a higher injury risk (Kumar, 2001; Vanrenterghem *et al.*, 2017). For example, Cormack *et al.* (2013), previously highlighted that lower limb neuromuscular fatigue in elite Australian Football players can implicate acceleration loads, and this is particularly prevalent on the z vector (–5.8% ± 6.1%). Similarly, when controlling for absolute load per minute, the reduction in the z vector was the largest (–5.1% ± 4.7%). It is well established that PlayerLoad™ and distance data are highly correlated due to the inclusion of vertical acceleration loads in the PlayerLoad™ algorithm (Boyd *et al.*, 2010). Thus, the findings of the present study together with those previously reported in other team sports, suggests that players with excessive levels of lower leg muscle recruitment under short periods of time (i.e., 1-week) may have a higher injury risk.

Although there was a lack of significance at the 99th percentile in this study, over 2-weekly cumulative periods, players who exhibited greater meters > 80% maximum velocity (e.g., high [2001 – 2545m] and very high [> 2454m]) were more likely to be injured compared to the reference group ($p < 0.05$). Similar findings were reported by Cummins *et al.* (2019) in elite Rugby League players. Authors reported that very-high speed distance was clearly associated with an increased injury risk. A point of consideration in the present study was that HSR distance showed an association with an increased injury risk over 2-week cumulative periods, whereas all workload groups for meters > 60% maximum velocity reported a reduced injury risk over 2-week cumulative periods. The difference between HSR distance and meters > 60% maximum velocity may be due to the more individualised method of percentage of maximum velocity, which has previously been reported as a key measure when investigating injury risk via running loads in contact team sport (Murray *et al.*, 2018; Weaving *et al.*, 2018). Importantly, it must be noted that these findings must be taken with a degree of caution given the high number of p-vales reported, and the lack of significance reported. Nevertheless, it may be worth future research investigating the relative and absolute demands of GPS speed zones further when monitoring workload and injury risk.

For instance, Murray *et al.* (2018), investigated the use of relative vs. absolute speed zones in Australian Football for injury risk analysis. A key finding was that very high-speed running distance significantly differed when data were expressed as an absolute measure compared to a relative measure based on each player's individual capacity. Authors found that slower players reported a significant increase in the amount of very-high speed running distance when expressed via a relative threshold compared to an absolute threshold. Contrarily, faster players reported a significant decrease in very-high speed running distance when expressed using a relative threshold compared an absolute threshold (Murray *et al.*, 2018). A key finding reported by Murray *et al.* (2018), was that slower players over an acute (1-weekly) period who completed a relative very high-speed running distance (1,500m) were 8.3 and 4.5 times more likely to be injured when compared to a relative very high-speed running distance of <500m and 501-1,000m, respectively. When using absolute thresholds however, no differences were reported between workloads. These findings suggest that slower players are simply unable to reach very high-speed distances when using an absolute measure, but also that these players may be significantly more likely to be injured when completing very high-speed running distance (relative to their individual capacity) over acute timeframes. Contrary to acute periods however, a noteworthy finding reported by Murray *et al.* (2018), was that greater absolute high-speed chronic (4-week) workloads were reported to increase the likelihood of injury for slower players (relative risk = 2.26). Greater relative high-speed chronic workloads however, decreased the likelihood of injury for slower players (relative risk =0.33). This finding suggests that a gradual and systematic increase in relative running distance may actually protect players against injury, and that relative measures that account for each individuals own capacity are important for monitoring player loads in relation to injury risk.

Similar to Murray *et al.* (2018), Colby *et al.* (2014), reported that 2-weekly "V1 distance" (individualised measure of total meters covered above the player's aerobic threshold speed [aerobic threshold calculated as blood lactate ~2mmol·L^{-1}]) >12,867m was associated with a 0.7 times lower injury risk than players with <10,321m V1 distance. The present study's findings, albeit not fully conclusive given a lack of significance, together with that reported by Murray *et al.* (2018) and Colby *et al.* (2014), may suggest that relative running thresholds could be an area for consideration when investigating the influence of GPS derived loads on injury risk.

Within the present study, there were no significant findings reported over 3-weekly periods. Contrary to this, Colby *et al.* (2014) reported that high 3-weekly cumulative loads were often highly associated with increased subsequent week injury risk for multiple workload variables. The authors reported that 3-weekly distance of 73,721-86,662m was associated with a 5.5 times greater injury risk compared to <73,721m in pre-season. In addition, sprint distance >1,453 m over 3-week cumulative periods trended towards a greater injury risk, compared with <864 m. During the in-season phase, a force load of >5,397 AU over 3-week cumulative periods was associated with a significantly higher injury risk when compared with force loads < 4,561 AU.

The findings in the present study compared to those reported by Colby *et al.* (2014), are likely attributed to a number of factors. Firstly, different sports will elicit different training and match demands and therefore a direct comparison between loads and injury is difficult. Secondly, the workload variables are slightly different between studies and thus different stimuli is likely to result in different physiological outcomes. Thirdly, Colby *et al.* (2014), reports a 3-week distance (73 – 86km) that is far greater than even the very high workload group (> 55, 053m) in the present study. Indeed, this can attributed to the fact that different sports were used (Australian Football vs. Rugby Union), but is also likely highly associated with the phase of the season in which this data was recorded. Pre-season training is an important phase of the season for players to maximise a number of physical attributes via high volume, high-intensity physical conditioning (Argus *et al.*, 2010). Thus, greater training volumes coupled with a higher training intensity would result in a much greater workload. Finally, the lack of data in the current study to assess these workloads in relation to the injury count may not have been great enough to provide sufficient power for the study.

There was no association between 4-weekly cumulative workloads and injury risk in the present study for any variable. Contrary to these findings, the protective effects of high 4-week workloads have commonly been reported in team sports research assessing cumulative and chronic loads on injury risk. For instance, using the sRPE method, Malone *et al.* (2016), reported that when previous training load was considered, players with chronic loading (average 4-week load) > 4750AU showed a protective effect against greater exposures to maximal velocity exercises compared to players with lower exposures (OR = 0.22). In addition, Cross *et al.*, (2016), reported a U-shaped curve for load vs. injury, such that intermediate workloads over 4-week periods were protective against injury compared to lower and higher workloads. Similar findings have been reported for external loading parameters. In elite Australian Footballers, Murray *et al.* (2017c), reported that, compared to a low 4-week chronic workload for total distance (5000m) and low-speed distance (2000m), high 4-week chronic workloads for total distance (>20,000m) and low-speed running (6000m) were associated with a lower injury risk. Furthermore, Cummins *et al.* (2019), reported that high 4-week total distance (> 60,000m) and PlayerLoad^{TM} (>3800 AU) were associated with a decreased injury-risk in the subsequent week. Beyond contact team sports, Jaspers *et al.* (2018), reported intermediate 4-weekly acceleration efforts reduced injury risk in professional soccer players. Similarly, Ehrmann *et al.* (2016), reported that in a cohort of professional soccer players, leading up to the occurrence of injury, players were exposed to a significantly lower 4-week average new body load compared to seasonal averages. Authors concluded that players might have been unable to cope with the high-intensity exercise bouts of competitive match play following periods of relative unpreparedness (Ehrmann *et al.*, 2016). Indeed, in Rugby Union it has been shown that greater exposure to high intensity events such as greater involvements in match play over a season can protect players from injury (Williams *et al.*, 2017b); thought to be due to appropriate level of match-specific fitness and physical robustness (Williams *et al.*, 2017b). Within the present study, no significant increases or decreases in injury risk over 4-week periods were reported. Therefore, the present study cannot support nor disagree with the aforementioned findings that provide evidence for the inclusion of 4-week periods across multiple contact and noncontact team sports.

4B.4.3 Chronic Loading and the ACWR

Research has recently investigated the coupling effect of low and high chronic workload combined with a player's ACWR status in relation to injury risk. When all chronic loads were combined within the present study, injury risk was significantly reduced for an intermediate high ACWR for acceleration meters > $2m{\cdot}s^{-2}$ (1.05 – 1.30) . It may be that a sufficient acceleration workload, that is high enough to induce physiological adaptations but not great enough to overwhelm the appropriate systems can reduce injury risk in a Rugby Union cohort (i.e., a high workload may cause unnecessary fatigue and a diminished workload capability, whilst a low workload may not be great enough to elicit the training adaptations needed to improve performance/reduce injury risk for a contact sport like Rugby Union). Indeed, numerous studies have reported an increased risk for higher ACWRs and a reduced injury risk for intermediate ACWRs. Murray *et al.* (2017c), reported that an ACWR > 2 was associated with a significant increase in injury risk for TD, HSR distance and player load when compared to an ACWR of 1.0 – 1.49 in elite Australian Football players. These players were 5 – 21 times more likely to be injured if the ACWR exceeded 2.0 compared to 1.0 – 1.49. In addition, Cummins *et al.* (2019), reported that elite Rugby League players who exceeded an acceleration ACWR of 1.4 were more likely to be injured compared to the (low workload) reference group. Within the present study, a low chronic workload combined with a low ACWR for HSR distance (0.52 – 0.88), significantly reduced injury risk also. Although future research is needed to cross examine the current findings in an elite Rugby Union cohort, it may be that low – intermediate pitch-based workloads are best for minimising injury risk in a contact team sport like Rugby Union, at least for acceleration and HSR parameters.

4B.4.4 Methodological Considerations and Limitations

The calculation of the ACWR via an uncoupled rolling average method was used based on recommendations from previous research (Lolli *et al.*,2019). It has previously been reported that the coupled rolling average method adds bias via the association between the numerator (acute) and denominator (chronic), and in particular, fails to normalise the numerator by the denominator (Impellizzeri *et al.*, 2020; Lolli *et al.*, 2019). Nevertheless, daily calculations via the exponentially weighted moving average may have been the most sensitive and thus best injury informing method, due to its ability to consider the decaying nature of fitness and fatigue over time (Murray *et al.*, 2017b; Williams *et al.*, 2016). Non-training weeks (through either a break week or injury) were excluded post data analysis to prevent the possibility of very low ACWRs (0s) being linked to injury. However, this was important to prevent the calculations inadvertently linking low ACWRs to a reduced injury risk. If possible, incorporating RPE values in conjunction with the session duration may have provided a more complete insight into the findings presented in this study. Similarly, a lack of anthropometric measurements, experience or fitness level differentiation, which have all been shown to improve/deteriorate athletic performance and have been linked to injury (Gabbett and Domrow, 2005; Malone *et al.*, 2017c; Esmaeili *et al.*, 2018), may have provided a more complete assessment of the load-related risk in this Rugby Union cohort. Rugby Union is a contact sport, and the majority of injuries occur during contact events or collisions. Therefore, a loading metric more associated with this aspect of the game may have provided important information regarding the risks associated with these events, however this study focused on locomotive load measures. Data was collected over 1-season only (other than total distance). Indeed, this may have resulted in findings that are more associated with a number of injured players, particularly when data was split into categories. Until future research can assess similar loading parameters in elite Rugby Union over multiple seasons with multiple teams, these findings should be taken with a degree of caution.

4B.4.5 Conclusion

The workload metric most associated with injury in this study was acceleration meters (> 2 $m \cdot s^{-2}$), which may highlight the utility of this workload metric when monitoring injury risk in an elite Rugby Union cohort. There were other potential avenues in which future research may also consider exploring, as the conclusions drawn from the current investigation are lacking but provide a glimpse into areas of potential interest. For example, a very high PlayerLoad™ over acute periods and very high weekly changes in TD were associated with an increased injury risk. It would be worth cross-examining the workload-injury relationships discussed in this study with more workload and injury data. Furthermore, there was a lack of other workload measures used in this study beyond the locomotive demands of Rugby Union. There are likely workload differences with regards to match volume and contact data also which is a limitation of the current study. Therefore, future studies may want to include a variety of workload metrics (i.e., match exposure, running/acceleration demands and contact demands) together when considering Rugby Union workload and injury risk.

CHAPTER 5

Quantifying Contact Load and Associated Injury Risk in Elite Scottish Rugby Union

5.1 INTRODUCTION

Professional Rugby Union match play is characterised by high intensity bouts of exercise, interspersed with periods of low intensity activity (Roberts *et al*., 2008). Although these high intensity bouts often involve intense locomotive activity (e.g., sprinting and accelerating), one of the most demanding aspects of Rugby Union is the physical nature of contact events. As a consequence of these highly demanding events, studies investigating the nature of match injury risk in professional Rugby Union consistently report a high proportion of contact related injuries (Brooks *et al*., 2005a; Whitehouse *et al*., 2016). In Rugby Union, the physical demands of contact vary considerably in terms of volume (i.e., duration of time spent in contact events per match) and intensity (i.e., number of contact events engaged in per match), depending on the positional group in which a player plays. For instance, scrummaging and mauling are two of the most physically demanding aspects of Rugby Union match play that - for the most part - last considerably longer than both tackling and rucking, and are nearly always performed by Forward positions (Props, Hookers, Second Row and Back Row players) (Roberts *et al*., 2008). Indeed, it is well established that Forwards engage in significantly more contact events (Roberts *et al*., 2008), resulting in a much higher contact volume per match (Roberts *et al*., 2008) than Back positions. Consequently, Forwards may need to possess a high physical tolerance and resilience to contact related fatigue and injury risk, yet the injury risk between Forwards and Backs are similar (Brooks *et al*., 2005a; Whitehouse *et al*., 2016).

Previous studies have highlighted fatigue as a potential risk factor for injury during Rugby Union match play (Burger *et al*., 2017; Hendricks & Lambert, 2014; Tierney *et al*., 2016). It may be that repeated contact trauma results in considerable structural damage to the muscle and soft tissue, thereby increasing a player's susceptibility to injury risk via a deterioration in the stress-bearing capacity of musculoskeletal tissue (Takarada, 2003; Williams *et al*., 2017a). Furthermore, fatigue may result in the deterioration of a player's skill execution, thereby hindering their ability to safely and effectively make the tackle (Gabbett, 2016b). These findings suggest that contact related fatigue on injury risk is multifactorial, and can be increased through both a diminished workload capacity, and a reduction in skill related attributes.

Previously, Hendricks & Lambert, (2014), suggested that there is an upper limit to a player's ability to engage in and continuously perform high energy impact tackles. This suggests that players with a poor workload capacity/inefficient tackling technique will lack the resilience needed to remain injury free, even at the professional level. This may be particularly important towards the end of match play when fatigue sets in, which can noticeably decrease tackling proficiency and an increase the risk of contact related injury (Hendricks & Lambert, 2014). In line with this, research in Rugby Union has previously reported injury risk to increase as players enter the later stages of match play (Burger *et al*., 2017; Tierney *et al*., 2016) . For instance, Burger *et al.* (2017), previously reported that injury risk was significantly higher in the 3rd and 4th quarters of Rugby Union match play compared to the 1st quarter. In addition, Tierney *et al*. (2016), reported that head impacts were most common in the 2nd half of Rugby Union match play, and particularly in the final quarter. Tierney *et al*. (2016), hypothesised that head impacts - and thus the risk of match concussion - was related to match fatigue. Importantly however, authors also reported that specific tackle characteristics not related to fatigue, were significantly associated with a higher injury risk. Authors reported that high speed into the tackle, the ball carrier's (BC) change in direction (for low body tackles) and the difference between the BC and tackler's body mass (for upper body tackles), to name a few, were significantly associated with head impact risk.

Previous studies report similar findings regarding the injury risk associated with particular contact events and the various characteristics associated with each contact event. For instance, Garraway & Macleod, (1995), previously reported that senior Scottish Rugby Union (SRU) players were more likely to be injured during tackling events (49% of all injuries), compared to all other contact events in Rugby Union match play. This has also been reported in more recent accounts of the professional game (Fuller *et al.*, 2008; Brooks *et al.*, 2005a). Indeed, at the professional level of Rugby Union there are around 450 contact events per match, in which tackling accounts for approximately 200 (Fuller *et al.*, 2007a). An important finding is that there is no significant difference between the number of injuries sustained by Backs and Forwards during match play (Brooks *et al*., 2005a; Whitehouse *et al*., 2016), even though Forwards experience much greater contact demands (Roberts *et al*., 2008). This suggests that Forward and Back positions are exposed to very different contact scenarios, that may originate from pre-tackle characteristics (e.g., distances from the BC/tackler or velocity on approach to the tackle) throughout the tackle phase (e.g., fending ability, impact force, leg drive etc.). It has previously been reported that Backs are more likely to be injured during tackling events, whereas Forwards are more likely to be injured during rucks and mauls (Brooks *et al.*, 2005a).

When investigating contact injury risk factors in Rugby Union, one of the most well-established methods is the use of match video analysis (Burger *et al.*, 2016; Cross *et al*., 2019; Fuller *et al*., 2010; Tierney *et al.*, 2016, 2018). For instance, Fuller *et al.* (2010), investigated injury risk factors associated with tackling in professional Rugby Union over 2 seasons involving 645 players from 13 English Premiership clubs. Using match video analysis, authors reported that a number of specific tackle-related characteristics were significantly associated with injury risk. For example, approaching the tackle at high-speed was identified as a significant risk factor for injury. In addition, tackle-phase characteristics such as a high impact force and/or collision events (i.e., tackling without use of the arms) significantly increased injury risk. The findings reported from this study suggest that there are clear characteristics associated with a higher injury risk in professional Rugby Union that may not necessarily be avoidable or related to match fatigue, and cannot be easily prevented. Collecting information on the contact related demands of elite Rugby Union will aid in our understanding of the physical demands of the game, how these demands relate to injury, and how injuries can be reduced.

In Rugby Union, understanding the contact demands of the sports and how contact events are related to injury is important. Indeed, the majority of Rugby Union injuries are a result of contact with another player. Yet, there are numerous methods employed to investigate the loading demands, and - in some cases - the injury risks associated with these workloads in Rugby Union. Beyond contact data, studies often include measures of training and match volume/exposure (Brooks *et al*., 2005a, 2005b; Brooks *et al*., 2008; West *et al*., 2019; Williams *et al*., 2017b), or the locomotive demands of the sport (e.g., total distance) (Cunniffe *et al.*, 2009; Cunningham *et al*., 2018; Pollard *et al.*, 2018; Reardon *et al.*, 2017). Depending on the measures used to track workload, the loading picture and injury risks reported will look very different between positional groups. For instance, it is well established that Back positions have greater locomotive demands, but that Forwards are involved in more contact events (Cunniffe *et al.*, 2009; Pollard *et al.*, 2018; Reardon *et al.*, 2017). Therefore, the measures adopted to investigate load will dramatically influence the workload-injury relationships reported.

Understanding the positional differences associated with various match workloads in Rugby Union and how these relative demands influence injury risk is important for developing relevant and match specific training practices that optimise each player's readiness for competition, thereby reducing potential injury risk in the modern game. The aim of the current study was therefore to investigate the demands and injury risk associated with contact events in professional Scottish Rugby Union matches (Section A) and to provide a comparison of injury incidence data from different workload measures adopted to monitor workload-injury relationships in professional Rugby Union (Section B). In order to achieve this aim, the following objectives were carried out:

- To quantify the positional demands of Rugby Union match play via contact volume and contact events engaged in per match (Section A).
- To investigate match contact patterns in relation to pitch location and match quarter (Section A).
- To assess the relative risks (RRs) of contact events through a comprehensive analysis of the various characteristics associated contact events in Rugby Union (Section A).
- To provide positional injury incidence data, calculated from match volume metrics, GPS data and video coding contact workload (Section B).

It was hypothesised that:

- Forward positions would engage in considerably more contact events and have a much greater contact volume compared to Back positions (Section A).
- There would be specific risks factors for injury from contact events, and these would differ depending on positional group (i.e., Forwards compared to Backs) (Section A).
- Injury incidence data between positional groups would be different depending on the workload measure used to calculate incidence values (Section B).

5.2A METHODOLOGY (SECTION A)

5.2A.1 Study Design and Participants

A prospective, observational cohort study design was employed to collect Rugby Union match play contact data via video analysis. Contact data were collected from 12 randomly sampled games, along with the time-loss injuries that occurred during these matches over the 2018/19 season for all first team players contracted to the Scottish Rugby Union's professional teams (Men's International Squad; Glasgow Warriors and Edinburgh Rugby). In total, data were collected from 94 players (Backs = 43; Forwards = 51).

5.2A.2 Video Analysis Coding

Prior to coding matches, an analysis framework (coding list) was created from a combination of sources and discussions. These included: 1.) The Scottish Rugby Union's match play coding list; 2.) Previous literature that had assessed the influence of contact events on injury risk (Fuller *et al.*, 2007a; Fuller *et al.*, 2010), and 3.) A series of discussions which took place involving a Rugby Union sports scientist, strength and conditioning coach, sports injury epidemiologist and sports scientist researchers. All variables were defined and grouped into various phases including: General; Ball Carrier and Tackler pre-tackle data; Ball Carrier and Tackler tackle phase data; Rucking; Mauling and Scrummaging. Each contact event in this study is expressed as per player. For example, if a ruck formed with 2 players contesting for the ball (from the teams involved in this study), this would be noted as 2 individual rucking events (1 per player).

In order to code all variables outlined in the analysis framework, a template was made up for each contact category (Ball Carrying [being tackled], Tackler [tackling the Ball Carrier), Rucking, Mauling and Scrummaging). Each template was coded independently to ensure all contact events could be coded with accuracy. Video footage was supplied by the SRU and uploaded onto NacSports Video Coding Scout PLUS Software (NACSPORTS VERSION 4.1.0, Gran Canaria). The same video analyst coded every tackle/collision, ruck, scrum and maul using a range of categorical variables related to the Ball Carrier and Tackler (T1 and T2, respectively). In line with Fuller *et al.* (2010), a tackle was defined as:

"*Any event where one or more tacklers attempted to stop or impede the BC whether or not the BC was brought to ground*."

For a more comprehensive breakdown of each categorical variable, see Table 5A.1.

Table 5A.1: Video analysis framework providing the description and instructions for all phases of play coded in this study, including multiple categorical variables for tackling, rucking, mauling and scrummaging.

Phase	Coding Variable	Definition	Instructions
General	Game Quarter	Quarter of the Game (1st, 2nd, 3rd, 4th)	Taken from of the game clock: **Quarter 1** = 0 - 20 minutes; **Quarter 2** = 20 - 40+ minutes; **Quarter 3** = 40 - 60 minutes; **Quarter 4** = 60 - 80+ minutes (Fuller *et al*., 2007a)
	Pitch Location	Location of the Pitch in which the player is currently within when he receives the ball (Defensive 22, 22 - 50, 50 - 22, Attacking 22)	Based on pitch dimensions: **0 - 22** metre line (Defensive 22); **22 - 50** metre line (22 metre line to halfway); **50 – 22** metre line (halfway line to 22 metre line); **22 – 0** (Attacking 22)
	Position	Playing position during the Game (Prop, Hooker, Lock, Flanker, Number 8, Scrumhalf, Stand Off, Centre, Wing, Fullback)	Position was registered based on shirt number (**Prop** = 1 & 3; **Hooker** = 2; **Locks** = 4 & 5; **Flankers** = 6 & 7; **Number 8** = 8; **Scrumhalf** = 9; **Stand Off** = 10; **Wingers** = 11 & 14; **Centre** = 12 & 13; **Fullback** = 15) and **Replacements** (16 - 23) based on the numbers substituted for (i.e., if 16 swaps for 2, then 16 is registered as a Hooker)
Pre-Tackle Phase (0.4s before contact, 2 frames for direction and velocity)	Movement Direction of Ball Carrier/Tackler	Direction the player is travelling with the ball (ball carrier) or towards the ball carrier (T1 or T2) (**Forwards** - towards oppositions try line; **Behind** - towards own try line; **Lateral** - running across/diagonally across the pitch)	The direction the ball carrier/tackler is facing was coded based on the direction the player was facing 0.4s before contact. This is measured only based on travelling direction, not where the placing is facing on the pitch (e.g., the tackler may be facing the oppositions try line but back tracking towards their own try line to get into the correct position to make the tackle. Thus, the player is moving backwards, but may make a front on tackle [see Direction of Tackle at the top of the tackle phase section below]).
	Velocity of Ball Carrier/Tackler	Velocity of the BC/T1/T2 (**Stationary** - Standing/Minimal Movement; **Slow** - Walking/Jogging pace; **Moderate** – Running; **Fast** - Sprinting)	Subjectively measured based on the velocity of the ball carrier/tackler into contact, approximately 0.4s before contact. Influenced largely by the distance of the ball carrier to the tackler and also when an evasive action is performed. Moderate was often coded when the player had enough room to pick up high speed, but not enough room to use their arms to propel themselves forward. In such cases, the BC would often maintain two hands on the ball to prevent a knock-on/turnover at the tackle phase. Fast was often coded when the BC had enough room to

		use their arms to propel themselves towards the opposition at a very-high velocity.
Pre-Possession Velocity	**Stationary** - Player did not adjust momentum for receiving the ball; **Accelerating with Intent** – The player receiving the ball began accelerating within 5 metres prior to receiving the ball; **Accelerating with Intent from Deep** – The player began accelerating beyond 5 metres out from receiving the ball, and was nearing maximum velocity	**Stationary** - Pick & Go's (i.e., a player picks the ball directly from the ground at the back of the ruck/maul and attacks the nearest space at the edge of the ruck/maul in an attempt to move the ball closer/beyond the gain line); Slow Ball off 9 (i.e., the player receives a slow ball from the Scrumhalf following a ruck, and has not started to accelerate until in possession of the ball. Stationary was also coded in any scenario where the player receiving the ball did not/could not accelerate until in possession of the ball following a line-out/ruck/maul, or if the player receiving a pass - or catching the ball following a kick -had not accelerated until in possession of the ball. **Accelerating with intent -** prior to having possession of the ball, the player had actively made an effort to begin accelerating within 5 metres of receiving the ball (i.e., accelerating as a teammate is about to pass the ball from a set-piece/already running to support a teammate before the ball is passed. **Accelerating with Intent from Deep –** coded if the player began accelerating beyond 5 metres out from receiving the ball, usually receiving a flat pass prior to entering contact at a high velocity.
Evasive Action on Receiving the Ball	**No Evasive Action Performed** (Ball-carrier continued in the same direction into the tackle from the moment they received the ball); **Side Step VM** (Ball-carrier performed an evasive step initiated by either leg with minimal change to velocity); **Side Step VA** (Ball-carrier performed an evasive step initiated by either leg that drastically reduced running velocity to evade T1/T2); **Arching Run** (Ball-carrier performed an arcing run)	**No Evasive Action -** coded if the player did not attempt to evade the oncoming tackle, and instead charged at the defender with intent. No Evasive Action was also coded if the player made a slight adjustment in direction on immediately receiving the ball, before accelerating, but thereafter continued in the same direction with intent of entering a contact scenario at a different angle, rather than trying to evade an oncoming tackle. **Side Step VM –** coded if ball-carrier performed an evasive step initiated by either leg with minimal change to velocity in an effort to evade an oncoming tackle following acceleration, or to evade an oncoming tackle where the player has not had time to accelerate, and thus velocity could not be altered regardless of the situation.

			Side Step VA – Coded when the ball carrier is running into a tackle, but drastically reduces running velocity, and initiates a side-step with either leg to evade the tackle – usually resulting in a much lower contact load than Side-step VM, due to the large difference in velocity into the tackle. **Arching Run** – coded when the ball carrier performed an arching run prior to contact, usually performed when a player has taken the ball following a set-piece
	Distance of Ball Carrier from T1/T2 Upon Receiving the Ball	**Pick & Go** (Forward at the back of the ruck picks up the ball and attacks the nearest space to move the ball closer to the gain line); **Near** (Ball-carrier was within 2 metres of T1/T2); **Moderate** (Ball-carrier was within 2-5 metres of T1/T2); **Far** (Ball-carrier was 5 metres+ from T1/T2)	**Pick & Go -** coded when a player at the back of the ruck picks up the ball and attacks the nearest space to move the ball closer to the gain line **Near -** coded when the ball-carrier was within ~ 2 metres of the tackler on receiving the ball **Moderate -** coded when the ball-carrier was within ~ 2-5 metres of the tackler on receiving the ball **Far** – coded when the ball-carrier was ~ 5 metres or beyond from the tackler on receiving the ball. **NOTE:** For T2 coding, the distance was coded as the distance the ball-carrier was from the second tackler once contact had been made with T1.
Tackle Phase	Direction of Tackle	Tackle direction from T1 or T2 in relation to BC. **Front -** BC was tackled front-on ; **Side -** BC was tackled from the right or left side; **Behind -** BC was tackled from behind; **Oblique -** BC was tackled from a diagonal, slanting angle	At the point of contact, 'front' was coded when the BC was tackled front-on by T1/T2; 'Side' was coded when the BC was tackled from the right or left side by T1/T2; 'Behind' was coded when the BC was tackled from behind by T1/T2; 'Oblique' was coded when the BC was tackled from a diagonal, slanting angle by T1/T2
	Sequence of Tackle	**1V1 -** Ball Carrier was tackled by T1; **Sequential -** T2 hit the BC whilst still being tackled by T1; **Simultaneous -** T1 and T2 hit the BC at the same time	Firstly, a tackle was defined as "any event where one or more tacklers attempted to stop or impede the BC whether or not the BC was brought to ground" (Fuller *et al.*, 2010). Thereafter, a 1V1 was coded when the BC was only in contact with one tackler throughout the tackle phase. Sequential was coded when the BC was initially hit by 1 tackler (T1), but while still in contact with T1, the BC was then in contact with T2 (out with 2 frames). Simultaneous was coded with the BC was hit by T1 and T2 within 2 frames of each other.

		NOTE: in scenarios where there was a 3rd tackler, the first tackle was coded as simultaneous/sequential - depending on the situation – and thereafter the 3rd tackler was coded as a 1v1, but a note was made to inform that this was a 3+ scenario.
Impact Force	The initial impact force a player was subjected to at the initiation of the tackle phase	Low was coded where the impact force of the tackle was perceived to have no real influence on the tackle load, such as a jersey tackle or tap tackle, or a tackle that was predominately achieved through leg drive rather than impact; Moderate was coded for when the impact force was perceived to be great enough to knock the player off balance; High was coded when the impact force was great enough to knock the player off their feet, or with a great enough force that both were abruptly impeded from the contact load, such as two players hitting front on (subjective)
Type of Tackle	**Tackle** - Ball Carrier was impeded/stopped by defending team who actively used their upper limbs; **Collision** - Ball Carrier was impeded/stopped by tackler without use of the arms; **Off The Ball Contact** – Player who did not have possession of the ball was tackled or collided with the opposition	**Tackle** was coded in an event where one or more tacklers attempted to stop or impede the BC with their arms, whether or not the BC was brought to ground (Fuller *et al.*, 2010). This was the case in when the BC was impeded to any degree from any contact with the opposition. A tackle was also coded if the Ball-carrier had been hit after immediately releasing the ball due to the defensive player already committing to the tackle. **Collision** was coded in an event where one or more tacklers attempted to stop or impede the BC without use of their arms, whether or not the BC was brought to the ground (Fuller *et al.*, 2007a; Fuller *et al.*, 2010). This was also coded if the Ball-carrier had been hit after immediately releasing the ball due to the defensive player already committing to the tackle. **Off The Ball Contact** was coded for when a defensive player tackled or collided with an attacking player who clearly did not have possession of the ball, and who was not already committed to the tackle - regardless of whether the action was penalised or not.
Fend	**Absent** - No Fend Attempted; **Moderate** – Fend was Efficient Enough to Disrupt a Tackle; **Strong** – Fend Prevented Tackle Success	**Absent** was coded when the BC maintained hands on the ball, or only used their arms to cushion ground impact; **Moderate** was coded when the BC clearly used their arms to disrupt the incoming tackle or during the tackle, but did not break the tackle.

	'Fend' encompassed: **Hand-Offs -** the Ball-carrier attempted to fully extend their non-ball-carrying arm by pushing outwards with the palm of their hand to disrupt/break the tackle. **Bump-Off/'Bosh'**– Ball-carrier lowered their body and leaned into the tackle in an attempt to dominate the collision/tackle. The ball-carrier may also have pushed out with their arm(s) to prevent the defender from successfully completing a tackle	**Strong** was used when the BC was able to prevent the tackle through fending, and was thus no longer in contact with the opposition. **Note:** The **Bump-Off/Bosh** variable was only included in the analysis if the player was actively seen trying to use their arms to disrupt/break the tackle, or of the bump-off was dominant enough to break the tackle. **Strong Bump Off/Bosh** was also used if the fend was strong enough to break the tackle (i.e., the defender was knocked backwards) but the ball carrier failed to remain upright, and consequently went to the ground.
Welding	Supporting Player binding to the ball carrier and actively driving the BC forward	The player was coded as welding if they actively connected to the BC and aimed to help drive them forward, through the tackle phase. In addition, the BC was coded as being driven through the tackle if a teammate attempted to weld.
Welding Time	Duration of time a player spent welding	Welding time was initiated at the point where the supporting player bound to the BC to drive the BC forwards up until the player ceased to do so, such as the BC going to the ground or losing the ball
Leg Drive	**Absent -** No Leg Drive Attempt, **Moderate** - Player was actively but not predominately using legs to support their efforts, **Hard -** Player was actively low, primarily driving with the legs	**Ball-carrier:** Absent was coded when the player made no effort to drive with their legs at any point throughout the phase following contact; Moderate was coded when the player was actively using their legs to assist but not predominately, such as to maintain balance/stay upright, but hips not lowered sufficiently, and not having to drive against the tackler; Hard was coded when the player was actively trying to drive forwards, trunk at an approx. 45' angle, hip low, gripping tightly to the attacking/defending player and clearly driving following contact. **Tackler:** Moderate was coded when the player was actively using their legs to assist but did not have to drink the attacking player back/prevent the attacking player making sufficient ground through predominately leg drive; Hard was coded when the defending player had to actively drive the opposition back following contact, or stop the Ball-carrier predominately through

			leg drive, such as lowering their trunk to an approx. 45' angle, hips low, gripping tightly to the attacking/defending player and clearly driving forward.
	Tackle Dominance	Ability of the player to continue moving in the desired direction pre-to-post tackle. **Positive** - Player continued moving in the same direction pre-to-post tackle (i.e., made positive ground); **Negative** - Player was hit in the opposite direction they were moving/facing pre-to-post tackle (i.e., player lost ground), **Neutral** - Player was stopped dead; **Lateral** - Player was moving forward but was hit laterally)	**Positive** was coded if, following the initial point of contact, if the BC/T1/T2 continue to move in the same direction as they entered the tackle (i.e., forwards). Positive was also coded if there was a miss-hit tackle and both the BC and tackler continued in the direction they entered the tackle. **Negative** was coded if the BC/T1/T2 are knocked in the opposite direction that they entered the tackle phase (i.e., if the BC and T1 are running towards each other and the BC is knocked back and T1 continues their momentum forwards following contact, then T1 is coded as positive and BC is coded as negative). **Neutral** was coded if the BC/T1/T2 do not progress in a positive or negative direction following the initial impact phase. Neutral was also coded if there was a miss-hit, and therefore the BC and tackler did not move in any particular direction due to contact from the tackle, or when both players collapsed onto their knees mid tackle and thus could not drive in any particular direction during the remainder of the tackle. **Lateral** was coded if the BC/T1/T2 do not continue in a positive or negative direction following impact, but do not come to a stop and instead fall to the side/in a lateral direction, or are spun around following the initial impact.
	Tackle Contact Time	Total minutes spent tackling	Time in seconds each player was involved in the tackle phase. It is registered from the moment contact is made until the player is brought to the ground, or has stopped actively engaging in the tackle phase. Tackle time is continued up until the point that active engagement in ceased. Therefore, even if the ball is passed and play continues, but the tackle is still in motion, then this is coded until the tackle has come to an end.
Rucking	Ruck Impact	**No Contact** - Player was at ruck but was not involved in contact; **Moderate** - Player entered the ruck to actively contest for/secure the ball, or clear the ruck; **Hard** - Player	Firstly, a Ruck was defined as a phase of play where one or more players from each team were on their feet, engaging in physical contact, and close around the ball on the ground. A ruck was coded for the moment the ball hit the ground, and where one or

	entered the ruck with significant dominance, such as a player from the attacking team knocking a defending player back or fending off players to secure or win possession of the ball	more players from each team were involved in contact to gain/maintain possession of the ball. If the player remained on their feet and was engaging in contact throughout, then they were coded throughout the rucking phase until the ball was played from the ruck. Coding was stopped the moment the ball was picked off the ground, or if the player went to the ground (and was thus no longer on their feet) during the ruck. If the player dis-engaged from contact or removed themselves from the ruck without going to the ground, then coding was also stopped for this player the moment contact ceased. If the player was not involved in contact and therefore also had no leg drive at the ruck, the player was coded but stopped on completion of filling out the data (i.e., the researcher did not wait until the end of the ruck due to no contact, and thus the duration being irrelevant from a loading perspective). If the player dis-engaged from the ruck and then re-entered, this was coded as two separate entries. **'No Contact'** was coded when a player entered an on-going ruck to protect the ball/support, but was not involved in contact with another player; **Moderate** was coded when the player entered the ruck and was actively engaged in contact to protect the ball/contest for the ball/clear the ruck but was not hit or did not hit the ruck with a high impact (subjective). Moderate was also coded in instances where the player made contact with the opposition but it was a 'miss-hit'; **Hard** was coded for when the player entered the ruck or was hit while in the ruck with an intentional high force and made solid contact with the opposition (i.e., was not a miss-hit, subjective).
Ruck Contest	**1V1 -** Player was involved in a 1V1 scenario, **2V1 -** player was contesting with 2 players before support was (or was not) provided, **3+V1 -** player was contesting against 3+ players before support was (or was not) provided	A 1V1 was coded when a player in the ruck was only in contact with one other player throughout the ruck phase; 2V1 and 3+V1 were coded when a player was hit simultaneously or sequentially by two (2V1) or more (3+V1) defending or attacking players during the ruck phase. If two players from the same team were contesting against 1 opposition player, then the contest was coded as 1V1 for each player.

	Player Role	**Attacking**: Protecting the ball, clearing the ruck, support, no active engagement; **Defensive**: Counter-ruck, Jackling, no active engagement	**Attacking (in possession of the ball)**: **Protecting the ball -** players over the ball preventing the defending team from turning the ball over; **clearing the ruck -** players actively driving the defending team out of the ruck; **support -** player who has entered the ruck and engaged in contact as support, but who is not clearing the ruck out or exclusively competing to protect the ball; **no active engagement -** player entered a contested ruck but did not actively engage in contact (i.e., standing over the ball as the scrumhalf comes in to pass the ball out) **Defensive (not in possession of the ball)**: **Counter-ruck -** players actively driving the attacking team out of the ruck to get to the ball; **Jackling** - the first support player who is actively trying to turn the ball over; **No Active Engagement** - player entered a contested ruck but was not actively involved in any contact with another player
	Leg Drive	**Absent -** No Leg Drive Attempt, **Moderate** Effort - Player was actively but not predominately using legs to support their efforts, **Strong -** Player was actively low, primarily driving with the legs to contest/secure the ball against attacking/defending team	**Absent** was coded when the player made no effort to drive with their legs at any point throughout the phase, following initial contact; **Moderate** was coded when the player was actively using their legs to assist but not predominately, such as pulling the attacking player back/not attempting to drive forwards, hips not lowered sufficiently, but actively using legs to assist; **Hard** was coded for when the player was actively trying to drive forwards, trunk at an approx. 45' angle, hip low, gripping tightly to the attacking/defensive player and clearly driving hard
Scrummaging	Positional Group in the Scrum	**Front Row** - numbers 1, 2 and 3; **Second Row -** numbers 4 and 5; **Back Row -** 6, 7 and 8	**Front Row** - numbers 1 - 3; **Second Row -** numbers 4 - 5; **Back Row** - 6 - 8. Replacements (16 - 23) were coded in their designated position depending on the number they were replaced for (i.e., if 2 was substituted for 16, then 16 would be coded as the front row in the scrum).
	Scrum Collapse/Restart	Scrum Collapsed, No Scrum Collapse; Scrum Restart	**'Scrum collapsed'** is coded if the scrum collapses during scrummaging; **'no scrum collapse'** is coded if the scrum did not collapse during scrummaging; **'Scrum Restart'** is coded when the scrum has to be restarted, and is thus used from the 2nd attempt onwards

	Duration of Scrum	Duration a player was actively engaged in the scrum	Duration of scrummaging for each player is coded from the moment the referee calls 'set' until the ball leaves the scrum
	Leg Drive	Degree of effort used to drive with the legs while in the scrum	**Low** – coded for when the player was using their legs to stabilise, but minimal effort used to contribute to driving forwards; **Moderate -** coded when the player was actively using their legs to assist, but maximal effort was not attained. The Back Row have been reported to produce the lowest force throughout the scrum compared to the Second and Front Row. Therefore, the Back Row were coded as Low/Moderate depending on the given scenario. **Hard** was coded for when the player was exhibiting maximal leg drive effort to win/secure possession of the ball (Second and Front Row). The Second and Front Row have been shown to report higher force production throughout the scrum, compared to the Back Row. However, the difference between the Front and Second Row for force production has been shown to be statistically insignificant (Quarrie & Wilson, 2000).
	Impact Force	The initial impact force a player was subjected to at the initiation of the scrum phase (when the referee calls 'set')	**High** – Front Row; **High** – Second Row; **Moderate** – Back Row.
	Dominance	**Positive -** Scrum progressed in the direction the player was driving (i.e., forwards); **Neutral -** the scrum was stagnant and the player was neither progressing forward or backwards; **Negative -** the scrum was moving against the direction the player was driving (i.e., backwards)	**Positive -** Scrum progressed in the direction the player was intentionally trying to drive it; **Neutral -** the scrum was stagnant and the player was neither progressing forward or backwards; **Negative -** the scrum was moving against the direction the player trying to drive it. If the scrum wheeled, the same coding variables were used, depending on the direction the player was moving. **Note**: if the scrum was neutral for a period of time before the player moved in a positive or negative direction, then the coding was based on the time that player was predominantly in a neutral/positive/negative direction.
Mauling	Player Role	**Jumper -** Player receiving the ball from the lineout throw; **Lifters/Ball Security-** Players who immediately bind to the jumper to prevent the defending team from disrupting	Firstly, a maul is only coded if 1. A maul is formed (for a maul to be formed there must be at least three players involved, including the ball carrier - who has not gone to the ground - an opponent holding the ball carrier and a team mate bound to the

		maul formation, **Drive maul forward -** Players who come in from the back to drive the maul; **Disrupt maul -** defensive players who immediately try and wedge through gaps to disrupt maul formation**; Defend channels -** players defending the channels	ball carrier), and 2. Players are on their feet, actively trying to drive towards the opposition's goal-line. Coding continued for each player until the ball was played from the maul, the ball carrier went to the ground, the referee blew his whistle, or the maul collapsed. If a player left the maul before it finished, the researcher stopped coding the player as soon as contact ceased. If the player then re-joined the maul, this was then coded as a separate entry. If a maul was formed during open play, then the thrower, jumper and lifter variables were not used. Instead, 'Ball-carrier' and 'Ball-Security' variables were used. Where this occurred, the ball-carrier was coded as entering a tackle until the maul had formed. At this point the coded tackle was ceased, and the remainder of the play was coded as a maul. **Attacking play**: The '**Thrower**' is coded if the player who throws the ball to the jumper and joins a formed maul; the '**Jumper**' is coded as the player who is lifted and receives the ball from the lineout throw; **Lifters** are coded as players who lift the jumper, and bind to the jumper to prevent the defensive team from disrupting the maul formation; a player is coded as coming in to '**Drive**' the maul if their role is to drive the maul forward (i.e., towards the defending teams try line); **Ball-carrier** was coded when a maul is formed during open play, and that player was carrying the ball; '**Ball Security'** was coded when attacking players bound to the Ball-carrier to prevent disruption of maul formation and secure the ball. **Defensive Play:** the '**Jumper**' is coded as the player who is lifted and attempts to steal the ball from the lineout; **Lifters** are coded as players who lift the jumper, and thereafter are likely to try disrupt the maul in an effort to prevent the attacking team from forming a maul; a player is coded as trying to **'disrupt' the maul'** if they immediately try and wedge through gaps to disrupt maul formation; a player is coded as attempting to **'Drive**' the maul if their role is to drive the maul forward (i.e., towards the attacking teams try line).

	Leg Drive	Absent - No Leg Drive Attempt, Moderate Effort - Player was actively but not predominately using legs to support their efforts, Strong Effort - Player was actively low, primarily driving with the legs to contest/secure the ball against attacking/defending team	**Absent** was coded when the player made no effort to drive with their legs at any point throughout the phase, following initial contact; **Moderate** was coded when the player was actively using their legs to assist but not predominately, such as pulling the attacking player back/not attempting to drive forwards, hips not lowered sufficiently, but actively using legs to assist; **Hard** was coded for when the player was actively trying to drive forwards, trunk at an approx. 45' angle, hip low, gripping tightly to the attacking/defensive player and clearly driving
	Dominance	**Positive -** Maul progressed in the direction the player was driving; **Neutral -** the maul was stagnant and the player was neither progressing forward or backwards; **Negative -** the maul was moving against the direction the player was driving.	**Positive -** Maul progressed in the direction the player was intentionally trying to drive it; **Neutral -** the maul was stagnant and the player was neither progressing forward or backwards; **Negative -** the maul was moving against the direction the player was trying to drive it. **NOTE**: the maul was coded for each player based on the time that player was predominantly in a neutral/positive/negative direction. For example, if the maul was moving forwards (positive direction) for 8 seconds, was then neutral for 4 seconds, and then began moving forwards again for another 6 seconds, the entire duration was accounted for, but was termed in the dominant direction (i.e., positive in this case)
	Duration of Maul	Duration a player was actively engaged in the Maul	Duration of the maul is based on the time each individual player entered the maul, until that player stopped actively engaging in the maul
	Maul Collapse	Maul Collapsed, No Maul Collapse	**'Maul Collapsed'** is coded if the maul collapses before the ball is played or before the maul breaks; **'No Maul Collapse'** is coded if the maul did not collapse throughout players engaging in a maul. Players are coded as collapsed/not collapsed depending on the overall scenario (i.e., if a player comes out of the maul before it collapses, this player is still coded as being involved in a collapsed maul).

5.2A.3 Data Storage and Cleaning

On completion of coding all contact events the data was exported from Nacsports into Microsoft Excel via the Nacsports MS Excel © (XLS Format 2) option. Any gaps (i.e., variables that were accidentally missed), were noted, and those contact events were re-assessed. This ensured all contact events were accounted for and accurately coded. A formula was then entered for the start time of each contact event:

=TIME(,LEFT(StartTime,FIND(":",StartTime)-1),RIGHT(LEFT(StartTime,FIND(":",StartTime)+2),2))+RIGHT(StartTime,2)/(24*60*60*100)).

And the end time of each contact event:

=TIME(,LEFT(EndTime,FIND(":",EndTime)-1),RIGHT(LEFT(EndTime,FIND(":",EndTime)+2),2))+RIGHT(EndTime,2)/(24*60*60*100).

The end time was then subtracted from the start time to work out the length of each contact event that occurred within the game (see Table 5A.2 for reference).

Table 5A.2: Visual indication of how each contact event duration was calculated.

Player Number	Start	Tackle Start	End	Tackle End	Contact Time (mm.ss.000)
12	01:17:92	01:17.920	01:19:29	01:19.290	00:01.370
9	01:23:88	01:23.880	01:24:46	01:24.460	00:00.580
8	10:40:04	10:40.040	10:40:63	10:40.630	00:00.590
1	10:46:50	10:46.500	10:47:58	10:47.580	00:01.080
6	10:46:71	10:46.710	10:47:67	10:47.670	00:00.960
8	16:25:00	16:25.000	16:26:08	16:26.080	00:01.080

The data was then exported into a master coding document so that all recorded contact events for all players across all of the games coded were stored in one place.

Once all templates had been checked and updated where necessary, the individual match templates were combined to give the total contact events and total contact volume for each match. These were then combined into one master database to give the total number of contact events and total contact volume for all 12 games. Each template was also combined so that all contact categories over the 12 games could be investigated together (e.g., all Scrummaging templates were combined into one master Scrummaging database, etc.). On completion of the contact database, GPS data from the 12 games was combined into a separate database also. This data had already been checked following Chapter 4B, but was cross checked with the video coding data to ensure all players were accounted for in both the contact and GPS database. There were occasions where there was GPS data but no contact data, this was further investigated and accurately accounted for. This only occurred where players came on late in the 4th quarter and did not engage in any contact (thus, there was no contact data for that given player). On completion of these data checks, all data was deemed accurate and ready for analysis.

Confidentiality and anonymity was ensured across each databases by using unique player codes that were protected via a password that only the researcher could gain access to. Similarly, the same codes were used across this study that were previously used in Chapter 3 and Chapter 4A to ensure cross checks to be conducted without putting player information at risk.

5.2A.4 Intra-Rater Reliability

Reliability and accuracy of the video analysis coding framework was conducted by randomly selecting one match from the 2018/19 Scottish Rugby Union season. Once this match had been selected, the video was uploaded onto Nacsports Scout PLUS Software. All players who were involved in the match and entered a contact scenario (i.e., BC, T1/T2, Rucking, Mauling or Scrummaging) were coded using the aforementioned analysis framework.

On completion of coding the match fully (pilot game 1), it was then re-coded using the same pre-determined categorical variables outlined in Table 5A.1 one month later (pilot game 2). This was deemed a sufficient length of time between coding the game initially, and then re-coding the game to prevent the likelihood of familiarisation influencing the results. On completion of coding the game for the second time, all contact events that were identified in pilot game 1 vs. pilot game 2 (and vice versa) were assessed. This included using the definitions described in Table 3 to evaluate the analyst's accuracy (analyst's ability to code the same contact events in both pilot games), sensitivity (true-positives and false-negatives) and specificity (true-negatives and false-positives) for all contact events (See Chapter 5, Results Section A). These definitions enabled an appropriate assessment of the analysis framework, as they provided the number of times the analyst coded each contact event correctly vs. incorrectly.

Where there were contact events which had not been identified in one of the pilot games but had been identified in the other; these were then assessed by an additional expert analyst who had not previously coded the game. This was to identify whether those particular contact events were true-positives, false-negatives, true-negatives or false-positives. On completion of this secondary assessment, these contact events were separated into the appropriate definition categories and all of the data was analysed. Each template was analysed separately to assess the accuracy, sensitivity and specificity of that particular template, as well as together to provide the overall utility of the analysis framework.

5.2A.5 Updating the Analysis Framework

While video analysis was conducted for the pilot study, the analysis framework was continually updated where gaps/inadequate detail was recognised. This was important because contact events (e.g., a tackle) can occur in various scenarios, meaning certain contact aspects may not occur or may be missed when providing the initial description for each variable. This allowed the utility and usability of the analysis framework to continually improve where possible. The instructions were then updated again on completion of intra-rater assessment for any contact events that included a false-negative or false-positive. This was to minimise the occurrence of these events for all future games that were coded (see Table 5A.3).

Table 5A.3: Definition of events used to calculate the sensitivity and specificity of the video analyst's ability to accurately code all contact events in professional Rugby Union match play.

Sensitivity (collision did occur)		**Specificity (collision did not occur)**	
True-positive The player was involved in a contact event and the analyst coded the contact event	False-negative The player was involved in a contact event and the analyst did not code the contact event	True-negative (Ruck Specific) The following conditions were met: (1) the player entered a contact scenario, (2) the player did not engage in contact and (3), the analyst reported no contact was engaged in	False-positive The player was not involved in a contact event and the analyst coded a contact event

5.2A.6 Power and Sample Size for Contact Events

A sample size calculation was conducted based on the tackle data. This is because the tackle was the most common contact event. The calculation was conducted so that the number of tackles needed to identify a statistically significant (absolute) difference between the injured and general play group of 10% in the frequency of occurrence of a risk factor from 260 time-loss match injuries could be determined. This was compared to the frequency of occurrence of a risk factor in the general play group of 30% (based on an average of 3.56 ± 0.73 risk factors per variable). This was based on 90% power and a 95% confidence level, resulting in 2823 tackles needing analysed. This was divided by 235 (average number of tackles taken from previous literature assessing Rugby Union match play [Fuller *et al.,* 2010]), resulting in 12 matches needing coded. These were randomly selected from all of the games completed throughout the 2018/19 season.

5.2A.7 The Recording of Injury Data and Injury Definitions

All injury data was in with the line methodology and definitions used in Chapter 3 and 4B. The same software was used to collect and record injury data (Microsoft Excel [Version 16]; Orchard Sports Injury Classification System [Version 10] [Rae & Orchard, 2007]). As per previous chapters (3 and 4B) an injury was defined as "*Any physical complaint, which was caused by a transfer of energy that exceeded the body's ability to maintain its structural and/or functional integrity, that was sustained by a player during a rugby match or rugby training*." (Fuller *et al.*, 2007b, p. 329). A fully inclusive time loss definition was also used for all injury data: "*any injury that prevents a player from taking a full part in all training activities typically planned for that day and/or match play for more than 24 hours from midnight at the end of the day the injury was sustained*" (Brooks *et al.*, 2008, p. 864). All injuries were recorded from the 12 games assessed in this study. Injuries were collected and recorded for total injuries (including contact and non-contact) and also contact injuries that could only be identified from video analysis.

5.2A.8 Data Analysis

Each match template (e.g., Edinburgh match 1, Glasgow match 1, Scotland match 1 etc.) was combined in excel for all contact scenarios (e.g., Ball Carrying, Tackling [1v1, simultaneous and sequential], Rucking, Mauling and Scrummaging). This allowed mean contact volume and contact events per match to be investigated and explored in relation to type of contact event, and SRU positional groupings, as well as pitch location and game quarter. Match volume was provided via Catapult Optimeye S5 GPS units (Catapult, OptimeyeS5, Melbourne, Australia), as per Chapter 3. Therefore, match volume was defined as: "*the total time a player was involved* *in match play, from either kick-off or from the moment the player was substituted onto the field, until the player was either substituted off the field, or the referee blew for full-time, excluding the half-time break".* If the player left the field due to foul play (i.e., yellow or red card), or was injured (i.e., head injury assessment or blood injury), then the volume of time they were side-lined was excluded from the match time.

5.2A.9 Statistical Analysis

Given the high proportion of injuries for Ball Carrying (see Results section 5.3.2), each risk factor was investigated for injury risk for all players, and then separately for Forwards and Backs, by determining the relative risk (RR). This was achieved by comparing the frequency of occurrence within each category (i.e., a forwards movement direction vs. a movement direction that was not forwards, see below for example), for both the general play population and the frequency of occurrence within the injured population. The RR, standard error and resulting 95% confidence intervals were calculated according to Altman, (1991), using Statistical Package for the Social Sciences (SPSS), Version 26.

$$Relative\ Risk = \frac{a/(a+b)}{c/(c+d)}$$

For example, using data from Table 5A.11 for Ball Carrying in a Forwards Direction for all players:

$$Relative\ Risk = \frac{16/(16+1289)}{4/(4+288)}$$

$$RR = 0.895$$

Where the frequency of occurrence is:

- Moving in a forwards direction in general play population = 1289
- Moving in a forwards direction in injured population = 16
- Moving in a direction that was not forwards (i.e., lateral or behind) in the general play population = 288
- Moving in a direction that was not forwards (i.e., lateral or behind) in the injured population = 4

For the RR data, a value equal to 1 indicated that there was no greater prosperity of that given risk factor to cause injury than expected by chance. An RR of < 1 indicated a lower prosperity to cause injury, whereas a value > 1 indicated a higher prosperity to cause injury. Differences between injured populations and the general play populations were considered significant if the 95% CIs did not include the value 1.00. For the RR data, *p* values were calculated via a two-tailed Z test (Fuller *et al.*, 2010) on Microsoft Excel. Significance was set at the 95th percentile.

5.2B METHODOLOGY (SECTION B)

For Section B, the same teams, players, contact data, injury data and injury definitions were used as per Section A.

5.2B.1 Data Analysis

As per section A, players were split into SRU positional groupings (Props, Hookers, Second Row, Back Row, Scrum Half, Stand Off, Centre and Back 3). Total and mean match distance was collected via GPS devices (Catapult Optimeye S5). Match distance was taken as the GPS reported distance covered by that player while on the field. Match volume was calculated using two methods: 1.) Number of players on the field (15) multiplied by the length of a Rugby Union match (80 minutes) and 2.) Using the GPS data as outlined in Section A of the methods. Contact volume was calculated via the video coding match contact duration column as per Section A. Contact events were calculated as outlined in Section A also. Contact events per 1000 meters was also calculated distance and contact data to provide loading differences between positional groups when these metrics are included within the calculation. For investigating injury, injury incidence was calculated as the number of match injuries per 1000 hours of match volume (Brooks *et al.*, 2005a; Brooks *et al.*, 2005b; West *et al.*, 2019). This was done for both match volume metrics and contact volume. For contact events, injury incidence is expressed as injuries per 10,000 contact events. All injury incidence data includes 95% confidence intervals.

5.3A RESULTS (SECTION A)

5.3A.1 Intra-rater Reliability

Of the 786 individual contact scenarios, 781 (99.3%) were true-positives in pilot 1 and 785 were true-positives (99.9%) in pilot 2. For Ball Carrying, there was a total of 174 contact events, of which 173 were true-positives in pilot 1 (and 1 false-negative), and 174 were identified in pilot 2 (including 3 false-positives for Welding that were removed). There was a total of 131 tackles made. Pilot 1 identified 130 (and 1 false-negative) and pilot 2 identified 128 tackles (3 false-negatives). Players entered a Rucking event 272 times. Pilot 1 reported 269 of these events (and 3 false-negatives). Pilot 2 identified all 272 Rucks. Players engaged in a Maul 129 times and Scrummaging 80 times. Pilot 1 identified all events for Mauling and Scrummaging. Pilot 2 identified 128 of the Mauling attempts (1 false-negative), and all Scrummaging events. Inter-rater reliability was deemed successful if over 95% of contact events were true-positives, which was achieved in this study.

5.3A.2 Match Injury Data

A total of 60 time loss (contact and non-contact) injuries were sustained during match play over the 12 coded games (Forwards = 30, Backs = 30). A total of 32 specific contact injuries were identified from the video footage (see Table 5A.4 for a breakdown of positional injuries related to each contact scenario for the 32 identified contact injuries).

Table 5A.4: Injuries by SRU positional groupings and match contact scenario.

Positional Group	Ball Carrying	Tackling	Rucking	Mauling	Scrummaging	Total Identified Injuries
Prop	3	0	0	0	1	4
Hooker	2	0	0	1	0	3
Second Row	0	0	1	0	0	1
Back Row	4	2	0	0	0	6
Scrum Half	0	1	0	0	0	1
Stand Off	0	1	0	0	0	1
Centre	3	1	0	0	0	4
Back 3	8	2	2	0	0	12
Total	**20**	**7**	**3**	**1**	**1**	**32**

5.3A.3 Positional Breakdown of Match Volume, Contact Volume and Contact Events

5.3A.3.1 Match Volume

Players spent a total of 279.06 hours in match play over the 12 coded games (collected via GPS devices, see Table 5A.5 for positional breakdown of total match volume and mean match volume per player).

Table 5A.5: Total match volume per SRU positional group and mean match volume per player within each Scottish Rugby Union positional group over the 12 coded games.

Positional Group	Total Match Volume (hours)	Mean Match Volume (hours)
Prop	39.76	0.80
Hooker	16.37	0.78
Second Row	36.21	1.17
Back Row	56.54	1.13
Scrum Half	19.21	0.80
Stand Off	24.17	1.10
Centre	43.63	1.21
Back 3	43.17	1.20
Total	**279.06**	**1.03**

5.3A.3.2 Contact Volume

Players spent a total of 7.8 hours engaging in contact events over the 12 coded games (collected via video coding, see Table 5A.6 for positional breakdown of total match contact volume).

Table 5A.6: Total contact volume per SRU positional group over the 12 coded games.

Positional Group	Total Contact Volume (hours)
Prop	1.81
Hooker	0.84
Second Row	1.84
Back Row	2.41
Scrum Half	0.08
Stand Off	0.11
Centre	0.35
Back 3	0.35

Second Row players reported the highest mean contact volume out of any positional group (3.07 [± 1.74] minutes per player, see Figure 5A.1 for mean contact volume for all events). Props and Hookers reported the lowest contact volume for Forward positions (2.26 [± 1.05] and 2.09 [± 1.26] minutes per player, respectively). Centres engaged in the highest contact volume for Back positions (0.60 [± 0.36] minutes per player), but this was still 5 times lower than Second Row players. Scrum Half players were involved in the lowest contact volume per match than any other positional group (0.23 [± 0.16] minutes per player).

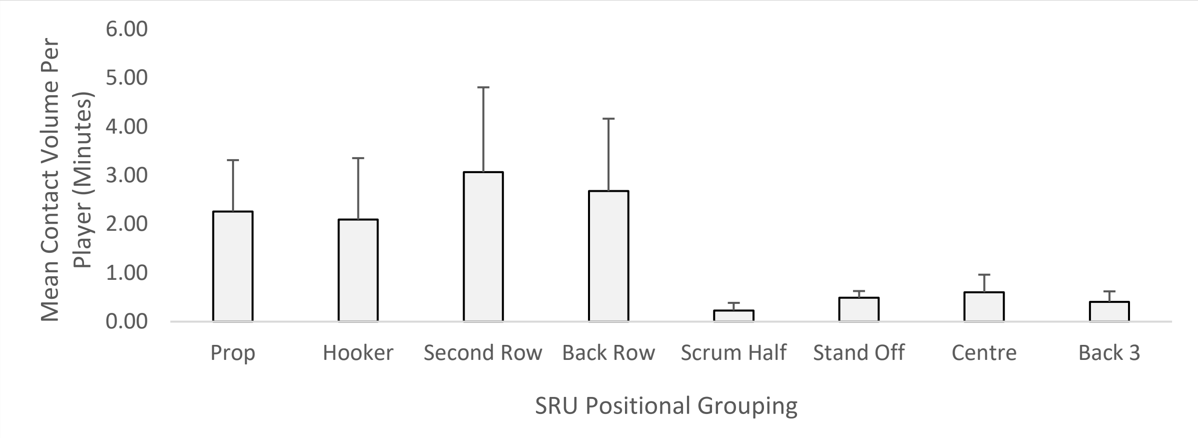


Figure 5A.1: Mean contact volume per match (minutes) per player for each SRU positional grouping.

NOTE: Errors bars, standard deviation.

When presented for Ball Carrying and Tackling events only, Back Row players reported the highest contact volume (24.31 [± 14.81] seconds), closely followed by Second Row players (22.27 [± 11.15], See Figure 5A.2). Centre and Stand Off players reported higher contact volumes (18.07 [± 11.53] and 18.58 [± 6.27] seconds per player per match, respectively), compared to Props (14.07 [± 8.53] seconds per player), and a similar contact volume to Hookers. Scrum Halves remained the lowest (8.10 [± 5.83] seconds per player).

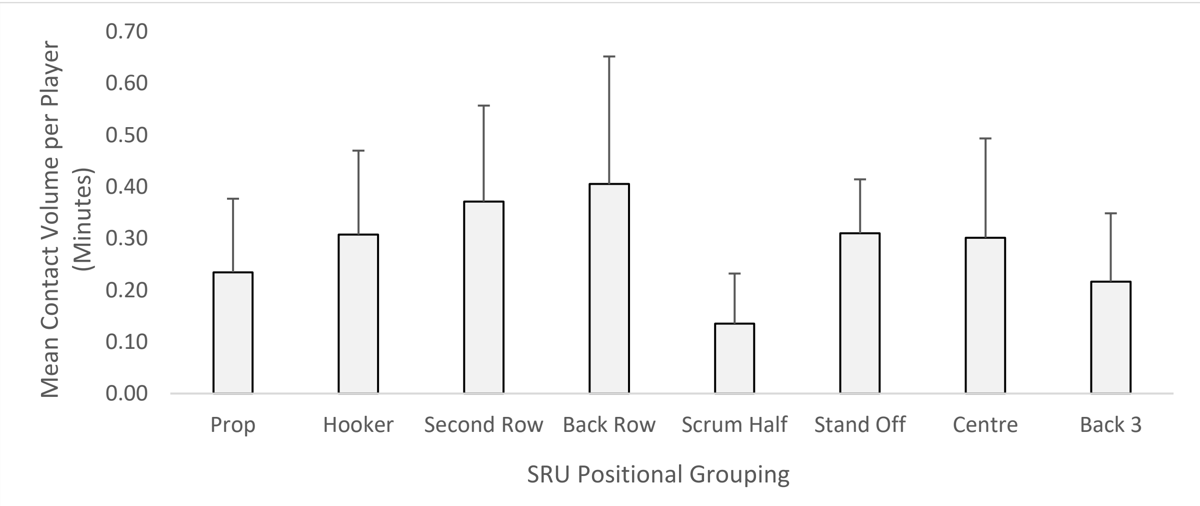


Figure 5A.2: Mean contact volume per match (minutes) per player for ball carrying and tackling (T1 and T2) for each SRU positional grouping.

NOTE: Errors bars, standard deviation.

The differences in overall contact volume between positional groups is explained by the increased contact volume Forwards are exposed to during Rucking, Mauling and Scrummaging (see Figure 5A.3). Forwards averaged 6.19 [± 1.82] minutes for Rucking, which was more than 3 times that of Backs (1.83 [± 0.46] minutes). Furthermore, Forwards averaged 12.50 [± 3.43] minutes for Mauling compared to 0.20 [± 0.16] minutes for Backs. In Rugby Union, Forwards engage in Scrummaging whereas Backs do not. Therefore, Forwards had a further 10.74 [± 2.48] minutes of high intensity Scrummaging per match over Backs.

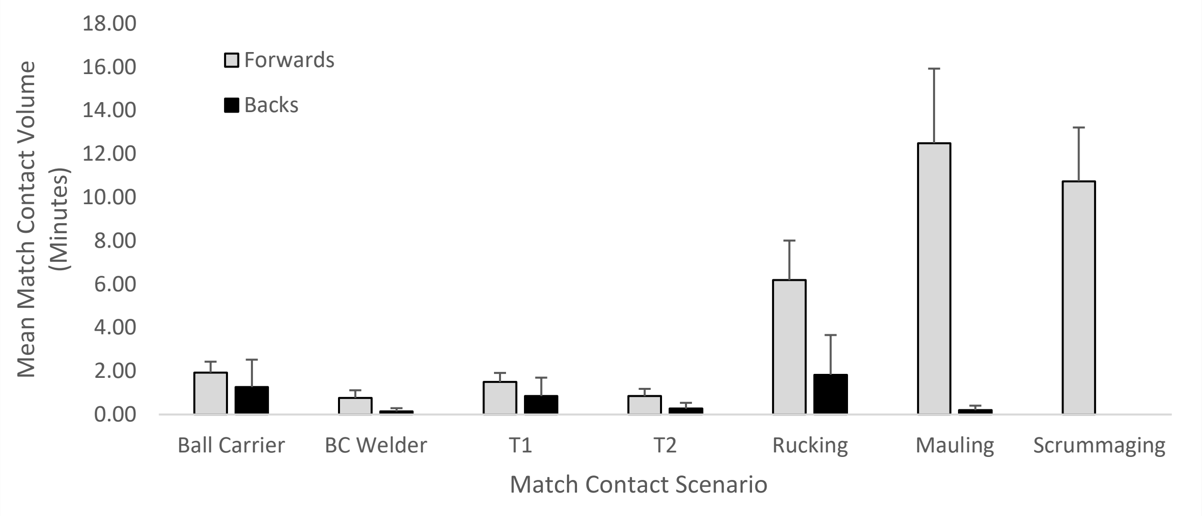


Figure 5A.3: A breakdown of mean contact volume for Forwards and Backs for each type of match contact scenario.

NOTE: Errors bars, standard deviation; T1, tackler 1; T2, tackler 2; BC, ball carrier.

From Table 5A.7 it can be seen that per event, Mauling and Scrummaging resulted in the highest contact volume per event, whereas Ball Carrying and Tackling were the lowest.

Table 5A.7: Mean contact volume per contact event.

Contact Scenario	Mean Contact Volume Per Event (*s*)
Ball Carrying	1.44 (± 0.99)
Tackling	1.21 (± 0.77)
Rucking	2.10 (± 1.48)
Mauling	9.63 (± 5.97)
Scrummaging	6.21 (± 2.95)

NOTE: s, seconds

5.2A.3.3 Contact Events

A total of 8954 contact events occurred over the 12 coded games. Total contact events per SRU positional grouping are provided in Table 5A.8).

Table 5A.8: Total contact events for Scottish Rugby Union positional groups over the 12 coded games.

Positional Group	Total Contact Events (n)
Prop	1741
Hooker	896
Second Row	1730
Back Row	2508
Scrum Half	199
Stand Off	287
Centre	821
Back 3	772

NOTE: n, number of contact events

Second Row players engaged in the highest contact events per match (48.1 [± 26.9]), closely followed by Back Row players (46.4 [± 24.7], see Figure 5A.4). Props and Hookers were involved in the lowest number of contact events per player per match for Forward positions, (36.3 [± 16.0] and 37.3 [± 20.6] contact events per player, respectively). For Back positions, Centres engaged in the most contact events per player (23.5 [± 13.9]), closely followed by Stand Off players (20.5 [± 3.4]). Scrum Halves had the lowest mean contact events per match (9 [± 5.2] contact events per player), followed by Back 3 players (15 [± 7.6] contact events per player).

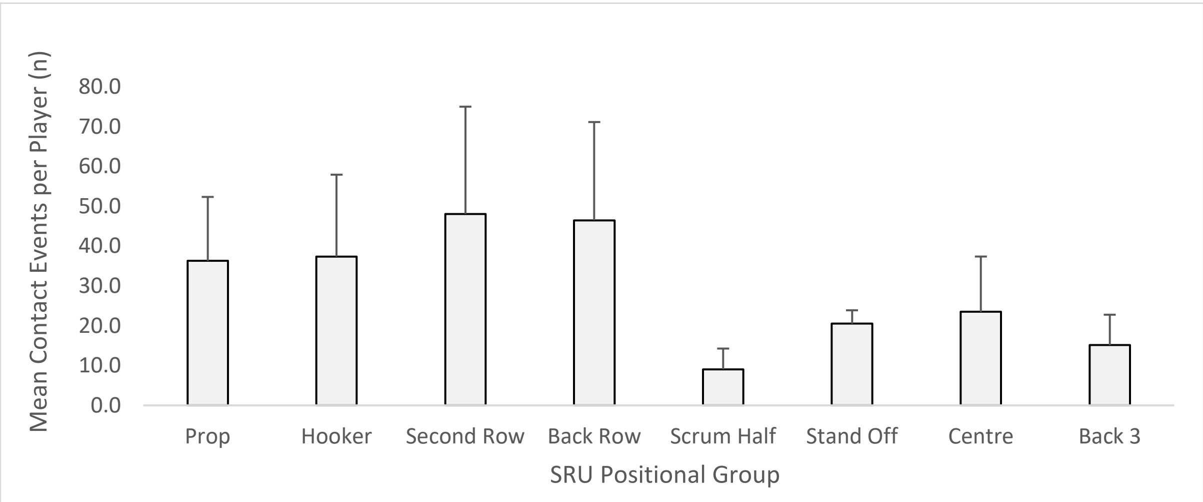


Figure 5A.4: Mean contact events per match (minutes) per player for each SRU positional grouping.

NOTE: Errors bars, standard deviation.

For Ball Carrying and Tackling events, Back Row players had the highest mean number of contact events per match per player (17.8 [± 10.3]), followed by Second Row players (17.1 [± 8.2], see Figure 5A.5). Stand Offs and Centre's were involved in more mean contact events per game (15.3 [± 2.9] and 14.7 [± 8.5] contact events per player, respectively) than both Props and Hookers (10.7 [± 6.0] and 13.9 [± 7.7] contact events per player, respectively). Scrum Half players engaged in the lowest mean events per game (6.6 [± 3.9]), followed by Back 3 players (9.8 [± 5.4]).

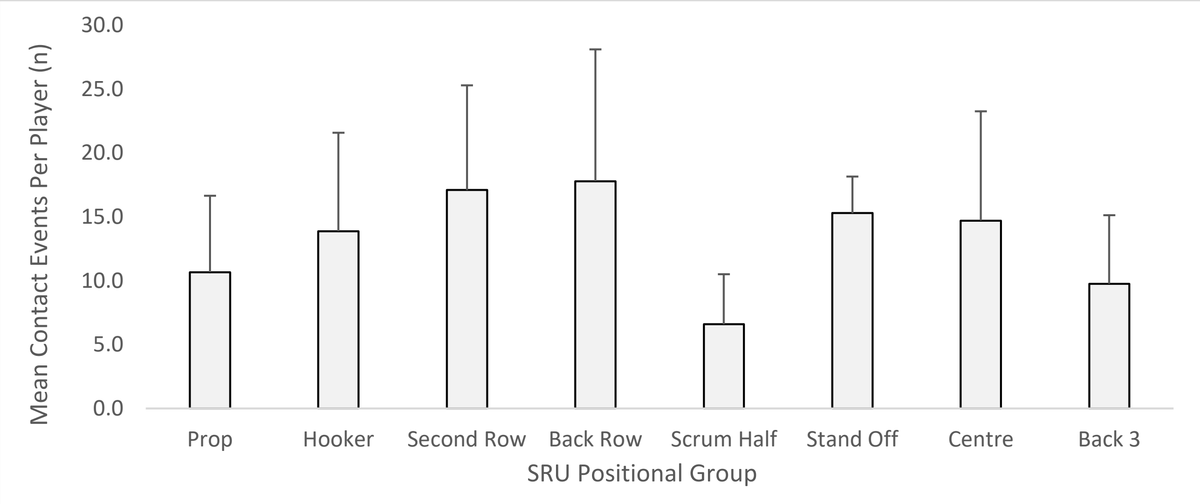


Figure 5A.5: Mean contact events per match (minutes) per player for ball carrying and tackling (T1 and T2) for each SRU positional grouping.

NOTE: Errors bars, standard deviation.

Forward positions entered a Rucking scenario 174.17 [± 35.07] times on average per match, compared to 54.83 [± 10.69] times for Back positions (see Figure 5A.6). Similarly, Forwards entered a Mauling scenario 77.17 [± 24.01] times compared to 2.25 [± 0.83] for Backs. Forwards were also the only players to engage in Scrummaging. Ball Carrying events were higher for Forwards (78.67 [± 18.13] events), but these events were the closest in terms of frequency of occurrence compared to Backs (54.33 [± 8.99] events). Tackling was also higher for Forwards for both T1 and T2 scenarios compared to Backs (Tackling as T1 = 75.25 [± 19.37] vs. 45.67 [± 8.90]; Tackling as T2 = 38.0 [±11.77] vs. 13.08 [± 5.06], respectively). Forwards were more likely to Weld the Ball Carrier through a tackling phase

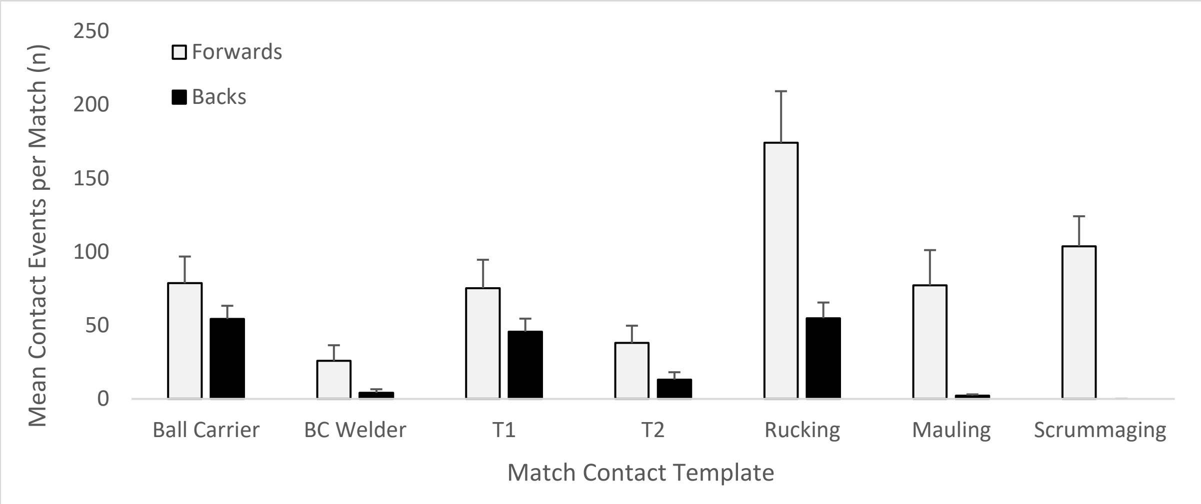


Figure 5A.6: Mean contact events for each contact template for Forwards and Backs over the 12 coded games.

NOTE: Errors bars, standard deviation; T1, tackler 1; T2, tackler 2; BC, ball carrier.

5.2A.3.4 Pitch Location

Mean contact volume and mean contact events for Ball Carrying were considerably lower inside each team's own 22m area (0.3 [± 0.16] minutes per match and 12.25 [± 7.26] events per match), compared to all other pitch locations (see Figure 5A.7 and 5A.8). Contrary to Ball Carrying, contact volume for Tackling was greatest inside team's own half (22 – 50m) for both T1 (0.95 [± 0.35] minutes) and T2 tackles (0.44 [± 0.20] minutes), and inside their own 22m area (T1 = 0.72 [± 0.40] minutes; T2 = 0.40 [± 0.26] minutes). This was also reported for mean Tackling events inside their own half (T1 = 50.17 [± 17.09] contact events; T2 = 20.42 [± 8.24] contact events) and inside their own 22m area (T1 =34.42 [± 18.09] contact events; T2 = 17.92 [± 11.29] contact events).

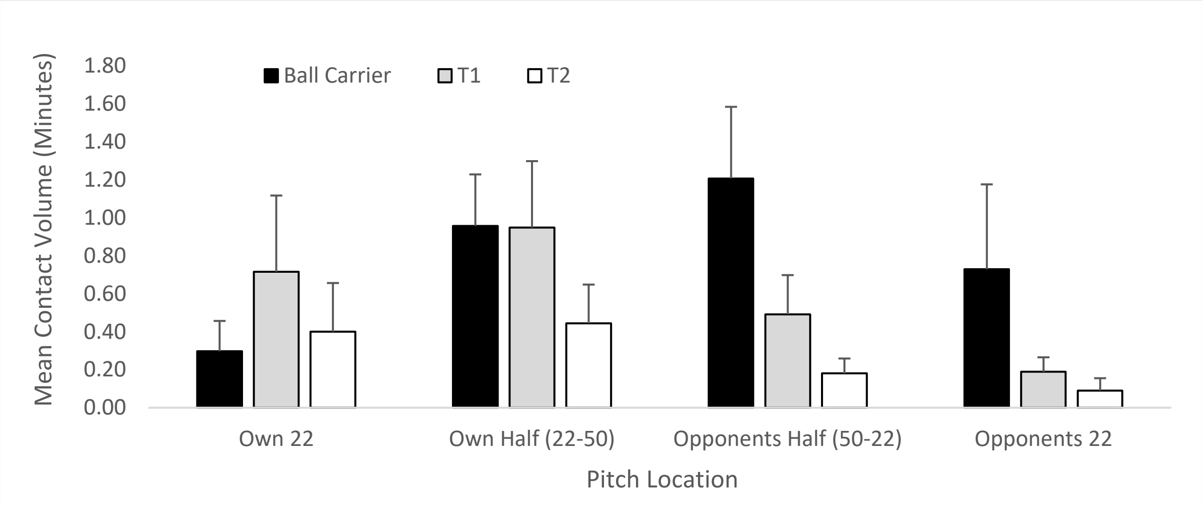


Figure 5A.7: Mean contact volume for ball carrying (BC), tackler 1 (T1) tackles and tackler 2 (T2) tackles based on pitch location.

NOTE: Black bars, ball carrying; grey bars, T1 tackles; white bar, T2 tackles; error bars, standard deviation.

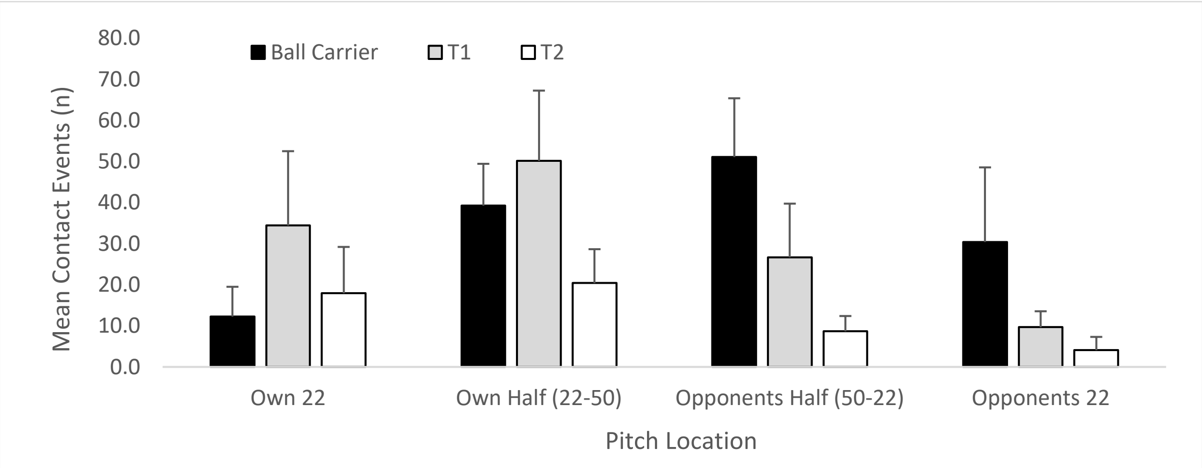


Figure 5A.8: Mean contact events for ball carrying (BC), tackler 1 (T1) tackles and tackler 2 (T2) tackles based on pitch location.

NOTE: Black bars, ball carrying; grey bars, T1 tackles; white bar, T2 tackles; error bars, standard deviation.

Rucking and Scrummaging were performed most within centre-field (player's and opposition's 22m – 50m, see Figures 5A.9 and 5A.10). Players engaged in a mean of 2.61 [± .1.08] minutes of Rucking and a mean of 4.39 [± 1.77] minutes of Scrummaging inside their own half, and a mean of 2.24 [± 0.94] minutes of Rucking and 2.69 [± 1.16] minutes of Scrummaging inside the oppositions half. Inside their own 22m area, players engaged in a mean of 1.50 [± 0.84] minutes of Rucking and 1.50 [± 1.63] minutes of Scrummaging. When in their opponent's 22m area, players engaged in a mean of 1.67 [± 0.91] and 2.15 [± 1.90] minutes of Rucking and scrummaging, respectively. Similar results were reported for contact events; players engaged in a mean of 72.0 [± 17.67] Rucking and 41.17 [± 17.01] Scrummaging events within their own half, and 71.83 [± 25.30] and 28.0 [± 11.55] Rucking and Scrummaging events in the opposition's half, respectively. This was compared to 37.92 [± 19.90] Rucking events 15.25 [± 16.72] Scrummaging events in their own 22m area, and 47.25 [± 26.25] Rucking events and 19.42 [± 17.79] Scrummaging events in the opposition's 22m area. Mauling was highest in the opposition's 22m area for both mean Mauling volume (4.90 [± 2.98] minutes per match) and mean Mauling events (26.92 [± 14.31] contact events). Mauling was lowest in teams own 22m area (contact volume = 2.11 [± 2.01] minutes; contact events = 15.08 [± 13.14]).

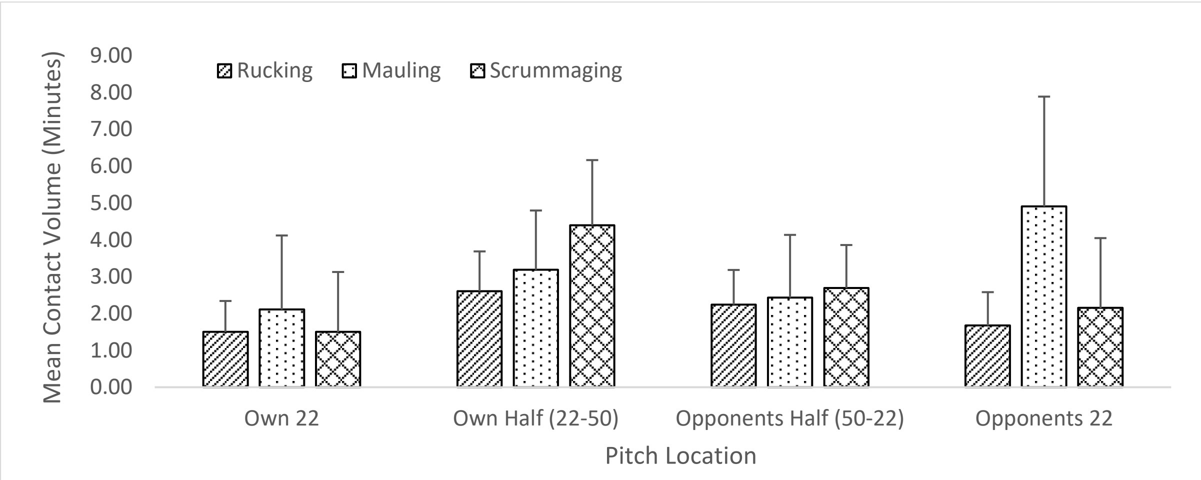


Figure 5A.9: Mean contact volume for rucking, mauling and scrummaging based on pitch location.

NOTE: Error bars, standard deviation.

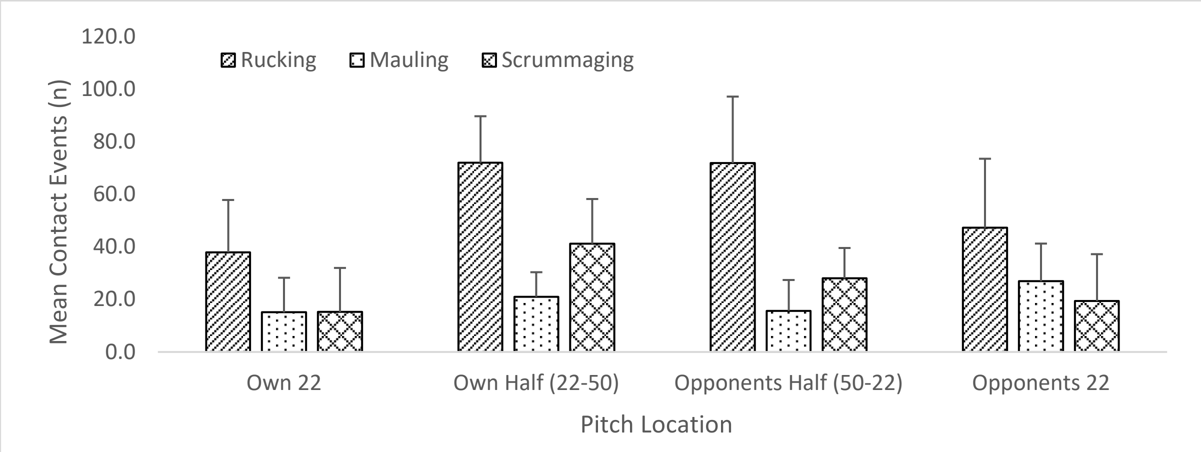


Figure 5A.10: Mean contact events for rucking, mauling and scrummaging based on pitch location.

NOTE: Error bars, standard deviation.

5.3A.4 The Injury Risk of Contact Events in Elite Scottish Rugby Union Match Play

5.3A.4.1 Game Quarter

Mean contact volume and mean contact events were highest in the 4^{th} quarter of match play (10.62 minutes [±1.80] and 203.33 [± 40.71] contact events, respectively, see Table 5A.9), followed by the 3^{rd} quarter (9.71 [± 2.15] minutes, 183.67 [± 30.49] contact events, respectively). Both contact volume and contact events were lower in the 1^{st} half of match play compared to the 2^{nd} half. There was a significant increase in the RR of injury for the 3rd quarter of match play (RR = 2.14, 95% CI 1.06 – 4.33, p=0.034). There was a trend for injury risk to be significantly higher in the 2^{nd} half of match play compared to the 1^{st} half (RR = 2.06, 95% CI 0.98 – 4.35, p=0.057).

Table 5A.9: Mean contact volume and contact events per match by game quarter with RRs.

Game Quarter	Mean Contact Volume Per Match (±SD)	Mean Contact Events Per Match (±SD)	RR (95% CIs)	P Value
Quarter 1	9.2 (± 2.36)	181.4 (± 23.59)	0.45 (0.16 – 1.28)	0.132
Quarter 2	9.4 (± 2.41)	177.8 (± 24.08)	0.72 (0.30 – 1.75)	0.475
Quarter 3	9.7 (± 2.15)	183.7 (± 30.49)	2.14 (1.06 – 4.33)	**0.034***
Quarter 4	10.6 (± 1.80)	203.3 (± 40.70)	1.04 (0.48 – 2.24)	0.927
1^{st} Half	18.62 (± 3.65)	359.2 (± 35.50)	0.49 (0.23 – 1.02)	0.060
2^{nd} Half	20.33 (± 2.46)	387.0 (± 48.20)	2.06 (0.98 – 4.35)	0.057

NOTE: RR, relative risk; CI, confidence intervals; *****, indicates significance < 0.05.

5.3A.4.2 Injury Risk for Contact Events

From the 12 matches analysed in this study, a total of 32 match injuries within the SRU medical database could be accurately identified following cross reference with match video footage. These 32 match injuries occurred during 5 types of contact events: Ball Carrying, Tackling, Rucking, Mauling and Scrummaging (see Table 5A.10). Of these injuries, Ball Carrying resulted in the greatest number of match contact injuries (20 contact injuries, 62.5%). From Table 4 it can be seen that Ball Carrying events have one of the shortest contact volumes per event in Rugby Union, lasting on average 1.44 seconds throughout tackle phase. This suggests that there are fundamental characteristics associated with Ball Carrying that cause injury beyond duration of the event. Indeed, from Table 7 it can be seen that the number of individual player contact events per injury was considerably lower for Ball Carrying (79.8 contact events per injury) than any other contact event (850.2 contact events per injury on average).

Table 5A.10: The number of contact events that ensued per identified injury event over the 12 coded matches in this study.

Contact Event	Individual player contact events (n)	Number of identified injuries (n)	Contact Events per Injury (n)
Ball Carrying	1596	20	79.8
BC Welder	356	0	N/A
Tackling	2064	7	294.9
Rucking	2748	3	916.0
Mauling	944	1	944.0
Scrummaging	1246	1	1246.0
Total	**8954**	**32**	**279.8**

Given the high injury risk for Ball Carrying in this study, these events were deemed worthy of more detailed investigation. Therefore, following tables provide the RRs with 95% CIs and p values for each Ball Carrying category (outlined in the methodology). See Table 8 for pre-tackle categories, Table 9 for BC vs T1 categories, and Table 10 for BC vs. T2 categories. Due to a small number of injuries identified for other contact events in this study (i.e., Tackling, Rucking, Mauling and Scrummaging), there could be no RR comparison between different contact events.

5.3A.4.3 Relative Risk – A Breakdown of Ball Carrying Events and Injury Risk

Pre-tackle

There were 6 pre-tackle circumstances that were shown to be significantly increase the RR of injury. These included a number of velocity categories (Velocity of BC vs T1, Velocity of T1, Velocity of BC vs T2 and Velocity of T2) and player movement directions (Movement Direction of BC vs T1 and Movement Direction of T1). When the velocity of BC vs T1 was fast, the relative risk of injury was significantly increased for Backs (RR = 9.83, 95% CI 2.14 – 45.11, p=0.003), but not Forwards (RR = 2.71, 95% CI 0.69 – 10.72, p=0.155, see Table 5A.11). Similarly, when the velocity of T1 on approach to the tackling event was fast, the relative risk of injury was significantly increased for Backs (RR = 5.45, 95% CI 1.64 to 18.09, p=0.006). Although both significant, when the BC approached the tackle at a 'fast' velocity, this resulted in a higher injury risk compared to when T1 approached the tackle fast.

For T2 tackles, Forwards were significantly more likely to be injured when the BC was approaching T2 at a fast velocity (RR = 10.86, 95% CI 1.57 – 75.26, p=0.029), but this was not reported for Backs (RR = 1.71, 95% CI 0.18 – 16.01, p=0.652). Similarly, when T2 approached the tackle at a fast velocity, Forwards were also significantly more likely to be injured (RR = 22.46, 95% CI 3.35 – 150.43, p=0.001), but Backs sustained no injuries when T2 was at a fast velocity. Contrary to Back positions vs T1, when T2 approached the tackle at a fast velocity for Forwards, this resulted in a higher injury risk than when the BC was at a fast velocity.

Movement direction of BC vs. T1 was significantly associated with injury risk when Back players were running behind (RR = 4.62, 95% CI 1.04 – 20.43, p=0.044). When the movement direction of T1 to BC was lateral, the relative risk for Forwards was significantly increased (RR = 5.86, 95% CI 1.59 – 21.58, p=0.008). When the movement direction of T1 vs BC was forwards, the relative risk of injury was significantly reduced for Forwards (RR = 0.37, 95% CI 0.15 – 0.88, p=0.027) but not Backs (RR = 0.63, 95% CI 0.20– 2.06, p=0.446).

Table 5A.11: Significant pre-tackle injury risk factors for ball carriers.

			No of events in group (%)		RR	
Risk factor			**General Play**	**Injured**	**Ratio (95% CI)**	**p Value**
Movement Direction of BC (vs T1)	Forwards	All Players	1289 (81.73)	16 (80.00)	0.90 (0.30 - 2.66)	0.860
		Forwards	814 (87.06)	9 (100.00)	0 (-)	-
		Backs	475 (73.99)	7 (63.64)	0.62 (0.18 - 2.10)	0.454
	Lateral	All Players	248 (15.73)	2 (10.00)	0.60 (0.14 - 2.56)	0.501
		Forwards	109 (11.66)	0 (0.00)	0 (-)	-
		Backs	139 (21.65)	2 (18.18)	0.81 (0.18 - 3.69)	0.797
	Behind	All Players	40 (2.54)	2 (10.00)	4.11 (0.99 - 17.16)	0.052
		Forwards	12 (1.28)	0 (0.00)	0 (-)	-
		Backs	28 (4.36)	2 (18.18)	4.62 (1.04 - 20.43)	**0.044***
Movement Direction of T1	Forwards	All Players	1094 (69.37)	9 (45.00)	0.37 (0.15 - 0.88)	**0.027***
		Forwards	728 (77.86)	4 (44.44)	0.23 (0.06 - 0.86)	**0.030***
		Backs	366 (57.01)	5 (45.45)	0.63 (0.20 - 2.06)	0.446
	Lateral	All Players	376 (23.84)	10 (50.00)	3.14 (1.32 - 7.48)	**0.010***
		Forwards	161 (17.22)	5 (55.56)	5.86 (1.59 - 21.58)	**0.008****
		Backs	215 (33.49)	5 (45.45)	1.64 (0.51 - 5.32)	0.416
	Behind	All Players	107 (6.79)	1 (5.00)	0.73 (0.99 - 5.37)	0.475
		Forwards	46 (4.92)	0 (0.00)	0 (-)	-
		Backs	61 (9.50)	1 (9.10)	0.95 (0.12 - 7.32)	0.965
Velocity of BC (vs T1)	Stationary	All Players	81 (5.14)	0 (0.00)	0 (-)	-
		Forwards	42 (4.49)	0 (0.00)	0 (-)	-
		Backs	39 (6.07)	0 (0.00)	0 (-)	-
	Slow	All Players	462 (29.30)	2 (10.00)	0.27 (0.06 - 1.17)	0.084
		Forwards	294 (31.45)	2 (22.22)	0.63 (0.13 - 2.99)	0.575
		Backs	168 (26.17)	0 (0.00)	0 (-)	-
	Moderate	All Players	694 (44.00)	6 (30.00)	0.55 (0.21 - 1.42)	0.222
		Forwards	455 (48.66)	4 (44.44)	0.85 (0.23 - 3.19)	0.820

		Backs	239 (37.23)	2 (18.18)	0.38 (0.08 - 1.74)	0.220
	Fast	All Players	340 (21.56)	12 (60.00)	5.31 (2.19 - 12.88)	**0.000****
		Forwards	144 (15.40)	3 (33.33)	2.71 (0.69 - 10.72)	0.155
		Backs	196 (30.53)	9 (81.82)	9.83 (2.14 - 45.11)	**0.003****
Velocity of T1	Stationary	All Players	650 (41.22)	10 (50.00)	1.42 (0.59 - 3.39)	0.440
		Forwards	448 (47.91)	6 (66.67)	2.16 (0.54 - 8.58)	0.279
		Backs	202 (31.46)	4 (36.36)	1.24 (0.37 - 4.19)	0.741
	Slow	All Players	610 (38.68)	4 (20.00)	0.40 (0.13 - 1.19)	0.105
		Forwards	364 (38.93)	2 (22.22)	0.45 (0.09 - 2.16)	0.330
		Backs	246 (38.32)	2 (18.18)	0.36 (0.08 - 1.67)	0.189
	Moderate	All Players	239 (15.16)	2 (10.00)	0.63 (0.15 - 2.68)	0.541
		Forwards	103 (11.02)	1 (11.11)	1.01 (0.13 - 7.99)	0.993
		Backs	136 (21.18)	1 (9.09)	0.38 (0.05 - 2.92)	0.357
	Fast	All Players	78 (4.94)	4 (20.00)	4.62 (1.58 - 13.51)	**0.005****
		Forwards	20 (2.14)	0 (0.00)	0 (-)	-
		Backs	58 (9.03)	4 (36.36)	5.45 (1.64 - 18.09)	**0.006****
Velocity of BC (vs T2)	Stationary	All Players	37 (4.72)	1 (12.50)	2.83 (0.36 - 22.43)	0.329
		Forwards	21 (4.05)	0 (0.00)	0 (-)	-
		Backs	16 (6.03)	1 (12.50)	4.94 (0.54 - 45.01)	0.155
	Slow	All Players	347 (44.32)	1 (12.50)	0.18 (0.02 - 1.47)	0.118
		Forwards	241 (46.53)	1 (25.00)	0.39 (0.04 - 3.68)	0.422
		Backs	106 (40.00)	0 (0.00)	0 (-)	-
	Moderate	All Players	314 (40.10)	3 (37.50)	0.90 (0.22 - 3.73)	0.893
		Forwards	214 (41.31)	1 (25.00)	0.48 (0.05 - 4.55)	0.534
		Backs	100 (37.74)	2 (50.00)	1.64 (0.23 - 11.44)	0.632
	Fast	All Players	85 (10.86)	3 (37.50)	4.79 (1.17 - 19.71)	**0.029***
		Forwards	42 (8.11)	2 (50.00)	10.86 (1.57 - 75.26)	**0.016***
		Backs	43 (16.23)	1 (12.50)	1.71 (0.18 - 16.01)	0.652
Velocity of T2	Stationary	All Players	322 (41.12)	4 (50.00)	1.43 (0.36 - 5.66)	0.623

	Forwards	237 (45.75)	3 (37.50)	3.53 (0.37 - 33.67)	0.276
	Backs	85 (32.08)	1 (12.50)	0.71 (0.08 - 6.72)	0.775
Slow	All Players	372 (47.51)	3 (37.50)	0.67 (0.16 - 2.77)	0.594
	Forwards	238 (45.95)	0 (0.00)	0 (-)	-
	Backs	134 (50.57)	3 (37.50)	2.89 (0.31 -27.44)	0.359
Moderate	All Players	84 (10.73)	0 (0.00)	0 (-)	-
	Forwards	41 (7.92)	0 (0.00)	0 (-)	-
	Backs	43 (16.23)	0 (0.00)	0 (-)	-
Fast	All Players	5 (0.64)	1 (12.50)	22.46 (3.35 - 150.43)	**0.001****
	Forwards	2 (0.39)	1 (12.50)	57.67 (8.14 - 408.61)	**0.000****
	Backs	3 (1.13)	0 (0.00)	0 (-)	-

NOTE: RR, Relative Risk; CI, Confidence Interval; ***,** Indicates significance < 0.05; ****,** Indicates significance < 0.01.

Tackle Phase - Ball Carrier vs Tackler 1

There were 3 T1 tackle-phase circumstances that were shown to significantly increase the RR of injury. These included: Tackle Type, Tackle Location, and Tackle Dominance. The relative risk of injury for tackling (compared to collisions and off the ball tackles) was significantly reduced for all players (RR = 0.09, 95% CI 0.02 – 0.36, p=0.001), and for Forward positions (RR = 0.04, 95% CI 0.01 – 0.18, p=0.000, see Table 5A.12). The RR for Backs cannot be reported due to these players not sustaining any collision or OTB injuries. Collisions and OTB tackles reported a significant increase in injury risk for all players (RR = 6.95, 95% CI 1.01 – 47.85, p=0.048; RR = 20.96, 95% CI 3.62 – 121.25, p=0.001, respectively), and this was also reported for Forwards separately (RR = 12.99, 95% CI 1.81 – 93.35, p=0.011; RR = 58.88, 95% CI 12.52 – 276.88, p=0.000, respectively). There was a trend towards high impact tackles significantly increasing the relative risk of injury for Forwards in this study (RR = 3.49, 95% CI 0.95 – 12.87, p=0.060), but not Backs (RR = 0.92, 95% CI 0.12 – 7.07, p=0.942).

When Forwards were hit side-on during the tackle phase, they were significantly more likely to be injured (RR = 4.65, 95% CI 1.26 – 17.16, p=0.021), however there was no relationship between tackle location and injury risk for Backs.

When Forwards were knocked laterally following the tackle contest the risk of injury was significantly greater for these players (RR = 5.71, 95% CI 1.46 – 22.38, p=0.012). There was no difference in injury risk for Backs for any tackle dominance categories.

Table 5A.12: Significant tackle-phase injury risk factors for ball carriers versus tacker 1.

Risk factor			No of events in group (%)		RR	
			General play	Injured	Ratio (95% CI)	p Value
BC Tackled Location						
	Front-on	All Players	722 (45.78)	8 (40.00)	0.79 (0.32 - 1.93)	0.620
		Forwards	502 (53.69)	3 (33.33)	0.43 (0.11 - 1.73)	0.232
		Backs	220 (34.27)	5 (45.46)	1.59 (0.49 - 5.14)	0.448
	Oblique	All Players	232 (14.72)	2 (10.00)	0.65 (0.15 - 2.77)	0.574
		Forwards	158 (16.90)	1 (11.11)	0.62 (0.08 - 4.90)	0.662
		Backs	74 (11.53)	1 (9.01)	0.77 (0.10 - 5.94)	0.814
	Side-on	All Players	400 (25.36)	8 (40.00)	1.94 (0.80 - 4.72)	0.144
		Forwards	195 (20.85)	5 (55.56)	4.65 (1.26 - 17.16)	**0.021***
		Backs	205 (31.93)	3 (27.27)	0.80 (0.22 - 2.99)	0.750
	Behind	All Players	223 (14.14)	2 (10.00)	0.68 (0.16 - 2.90)	0.614
		Forwards	80 (8.55)	0 (0.00)	0 (-)	-
		Backs	143 (22.27)	2 (18.18)	0.78 (0.17 - 3.56)	0.762
Tackle Impact	Low	All Players	714 (45.28)	9 (45.00)	0.99 (0.41 - 2.37)	0.984
		Forwards	318 (34.01)	2 (22.22)	0.56 (0.12 - 2.67)	0.473
		Backs	396 (61.68)	7 (63.64)	1.09 (0.32 - 3.67)	0.898
	Moderate	All Players	628 (39.82)	6 (30.00)	0.65 (0.25 - 1.69)	0.384
		Forwards	445 (47.59)	3 (33.33)	0.55 (0.14 - 2.20)	0.402
		Backs	183 (28.50)	3 (27.27)	0.94 (0.25 - 3.51)	0.933
	High	All Players	235 (14.90)	5 (25.00)	1.89 (0.69 - 5.14)	0.216
		Forwards	172 (18.39)	4 (44.44)	3.49 (0.95 - 12.87)	0.060
		Backs	63 (9.82)	1 (9.01)	0.92 (0.12 - 7.07)	0.942
Tackle Type	Tackle	All Players	1563 (99.1)	18 (90.00)	0.09 (0.02 - 0.36)	**0.001****
		Forwards	926 (99.04)	7 (77.77)	0.04 (0.01 - 0.18)	**0.000****
		Backs	637 (99.22)	11 (100.00)	0 (-)	-
	Collision	All Players	11 (0.70)	1 (5.00)	6.95 (1.01 - 47.85)	**0.048***

		Forwards	8 (0.85)	1 (11.11)	12.99 (1.81 - 93.35)	**0.011***
		Backs	3 (0.47)	0 (0.00)	0 (-)	-
	Off The Ball	All Players	3 (0.19)	1 (5.00)	20.96 (3.62 - 121.25)	**0.001****
		Forwards	1 (0.11)	1 (11.11)	58.88 (12.52 - 276.88)	**0.000****
		Backs	2 (0.31)	0 (0.00)	0 (-)	-
BC Tackle Dominance	Neutral	All Players	215 (13.63)	1 (5.00)	0.34 (0.05 - 2.50)	0.283
		Forwards	133 (14.22)	1 (11.11)	0.76 (0.09 - 5.99)	0.810
		Backs	82 (12.77)	0 (0.00)	0 (-)	-
	Positive	All Players	1064 (67.47)	13 (65.00)	0.90 (0.36 - 2.23)	0.832
		Forwards	657 (70.27)	5 (55.56)	0.53 (0.14 - 1.97)	0.352
		Backs	407 (63.39)	8 (72.73)	1.53 (0.41 - 5.71)	0.538
	Lateral	All Players	148 (9.38)	3 (15.00)	1.69 (0.50 - 5.70)	0.405
		Forwards	73 (7.81)	3 (33.33)	5.71 (1.46 - 22.38)	**0.012***
		Backs	75 (11.69)	0 (0.00)	0 (-)	-
	Negative	All Players	150 (9.52)	3 (15.00)	1.67 (0.49 - 5.62)	0.418
		Forwards	72 (7.70)	0 (0.00)	0 (-)	-
		Backs	78 (12.15)	3 (27.27)	2.65 (0.72 - 9.78)	0.143

NOTE: RR, Relative Risk; CI, Confidence Interval; ***,** Indicates significance < 0.05; ****,** Indicates significance < 0.01

Tackle Phase - Ball Carrier vs Tackler 2

There was one T2 tackle-phase circumstance that significantly increased the RR of injury. This was Tackle Dominance. When the Ball Carrier lost the tackle contest and was knocked negatively following contact with T2, Forwards were significantly more likely to be injured (RR = 9.24, 95% CI 1.33 – 64.17, p=0.024, see Figure 5A.13). In line with this finding, Forwards were also significantly more likely to be injured when T2 continued in a positive direction following contact with the BC (RR = 12.20, 95% CI 1.28 – 116.12, p=0.029). There was no relationship between tackle dominance for BC or T2 and injury risk for the Backs.

There was a smaller proportion of injuries for T2 categories, therefore the injury risk of some categories could not be explored. For instance, for BC fending, all injuries occurred when both Forwards and Backs did not attempt any type of fend. However, the relative risk of no fend vs. fending, or for each type of fend cannot be assessed due to a lack of injury data.

Table 5A.13: Significant tackle-phase injury risk factors for ball carriers versus tacker 2.

			No of events in group (%)		RR	
Risk factor			**General play**	**Injured**	**Ratio (95% CI)**	**p Value**
BC Tackle Dominance	Neutral	All Players	198 (25.28)	1 (12.5)	0.43 (0.05 - 3.43)	0.442
		Forwards	144 (27.80)	0 (0.00)	0 (-)	-
		Backs	54 (20.38)	1 (25.00)	1.30 (0.14 - 12.23)	0.829
	Positive	All Players	425 (54.28)	4 (50.00)	0.84 (0.21 - 3.35)	0.817
		Forwards	271 (52.32)	2 (50.00)	0.91 (0.13 - 6.42)	0.931
		Backs	154 (58.11)	2 (50.00)	0.72 (0.10 - 5.07)	0.756
	Lateral	All Players	80 (10.22)	0 (0.00)	0 (-)	-
		Forwards	54 (10.42)	0 (0.00)	0 (-)	-
		Backs	26 (9.81)	0 (0.00)	0 (-)	-
	Negative	All Players	80 (10.22)	3 (37.50)	5.12 (1.25 - 21.03)	**0.023***
		Forwards	49 (9.46)	2 (50.00)	9.24 (1.33 - 64.17)	**0.024***
		Backs	31 (11.70)	1 (25.00)	2.47 (0.27 - 23.03)	0.433
T2 Tackle Dominance	Neutral	All Players	272 (34.74)	1 (12.50)	0.27 (0.03 - 2.29)	0.239
		Forwards	187 (36.10)	0 (0.00)	0 (-)	-
		Backs	85 (32.07)	1 (25.00)	0.71 (0.08 - 6.72)	0.775
	Positive	All Players	178 (22.73)	4 (50.00)	3.35 (0.85 - 13.25)	0.084
		Forwards	100 (19.30)	3 (75.00)	12.20 (1.28 - 116.12)	**0.029***
		Backs	78 (29.43)	1 (25.00)	0.80 (0.09 - 7.60)	0.854
	Lateral	All Players	165 (21.07)	1 (12.50)	0.54 (0.07 - 4.34)	0.570
		Forwards	105 (20.27)	0 (0.00)	0 (-)	-
		Backs	60 (22.64)	1 (25.00)	1.14 (0.12 - 10.73)	0.916
	Negative	All Players	168 (21.46)	2 (25.00)	1.22 (0.25 - 5.98)	0.818
		Forwards	126 (24.32)	1 (25.00)	1.04 (0.11 - 9.88)	0.975
		Backs	42 (15.85)	1 (25.00)	1.75 (0.19 - 16.45)	0.636

NOTE: RR, Relative Risk; CI, Confidence Interval;***,** Indicates significance < 0.05; ****,** Indicates significance < 0.01

5.3B RESULTS (SECTION B)

5.3B.1 Player Load - A Comparison of Methods for Investigating Match Load and Injury Risk

Over the 12 games coded in this study, mean distance covered by Back positions was higher than all Forward positions, other than for Scrum Half players (see Table 5B.1). On the other hand, mean contact events per match was higher for all Forward positions compared to any of the Backs. Hookers had the 2nd lowest mean match distance (3,178m) and mean contact events per match (37.3 events) for Forward positions. Yet, these players performed more contact events per 1000m during match play than any other positional group in this study (13.4 events per 1000m).

Table 5B.1: Distance and contact data from the 12 games coded in this study.

Position	Total Distance (m)	Mean Distance (m)	Total Contact Events (n)	Mean Contact Events (n)	Contact Events per 1000m (n)
Prop	149,420	2988.4	1741	36.3	11.7
Hooker	66,729	3177.6	896	37.3	13.4
Second Row	144,349	4656.4	1730	48.1	12.0
Back Row	226,163	4523.3	2508	46.4	11.1
Scrum Half	88,421	3844.4	199	9.0	2.3
Stand Off	111,393	5304.4	287	20.5	2.6
Centre	193,374	5371.5	821	23.5	4.2
Back 3	186,573	5182.6	772	15.1	4.1

NOTE: m, distance in meters; n, number of contact events.

Second Row players reported the highest mean match distance compared to all other Forward positions. As aforementioned, these players also reported the highest number of mean contact events per match than any other positional group. However, these players reported the lowest incidence of injury for every single workload metric (match volume data, contact volume data and contact events, see Table 5B.2) out of all Forward positions. Hookers reported the highest match injury incidence rates out of all Forward positions for every workload metric. These players were also involved in the greatest number of contacts per 1000 metres.

Centre and Back 3 players had very similar GPS match volumes (43.63 and 43.17 hours, respectively), but incidence per 1000 hours was much higher for Back 3 players (183.4 [95% CI 68.5 - 298.2] vs. 347.5 [95% CI 205.4 - 489.5] injuries per 1000 hours, respectively, see Table 5B.2). Furthermore, these players were involved in a similar number of contact events

(821 vs. 772, respectively), but the injury incidence per 10,000 tackle events was much higher for Back 3 players (97.4 [95% CI 30.2 – 164.6] vs. 194.3 [95% CI 96.7 – 291.7], respectively). In relation to section A of this study, this data suggests that it is crucial to understand the nature of the load players are exposed to during Rugby Union when investigating injury risk. In this study, Centres had a greater contact volume and engaged in more contact events per match than Back 3 players (see Section A). Yet Back 3 players reported much higher injury incidence values. Indeed, this finding suggests that rather than total match load being the contributing factor to injury for these players, it may be more associated with the nature of the event.

Table 5B.2: A comparison of methods used to investigate injury risk in professional Rugby Union

Positional Group	Total Injuries	Total Match Time (hours)	Incidence (per 1000 hours)	95% CIs	GPS Volume (hours)	Incidence (per 1000 hours)	95% CIs	Total Contact Volume (hours)	Incidence (per 1000 hours)	95% CIs	Total Contact Events (n)	Incidence (per 10,000 events)	95% CIs
Prop	8	32	250.0	99.9 - 400	39.76	201.2	76.6 - 325.8	1.81	4419.9	0 - 10084	1741	46.0	14.2 - 77.7
Hooker	5	16	312.5	85.4 - 539.6	16.37	305.4	82.3 - 528.6	0.84	5952.4	0 - 17563.4	896	55.8	7.0 - 104.6
Second Row	5	32	156.3	30.4 - 282.1	36.21	138.1	25.7 - 250.5	1.84	2717.4	0 - 5838.9	1730	28.9	3.6 – 54.2
Back Row	12	48	250.0	127.5 - 372.5	56.54	212.2	105.7 - 318.8	2.41	4979.3	0 - 10599.2	2508	47.8	20.8 – 74.9
Scrum Half	3	16	187.5	-3.8 - 378.8	19.21	156.2	-6.2 - 318.5	0.08	37,500.0	0 - 293873.5	199	150.8	-18.5 – 320.1
Stand Off	4	16	250	37.8 - 462.2	24.17	165.5	17.3 - 313.7	0.11	36,363.6	0 - 248283.6	287	139.4	3.7 – 275.0
Centre	8	32	250	100 - 400	43.63	183.4	68.5 - 298.2	0.35	22,857.1	0 - 96907.9	821	97.4	30.2 – 164.6
Back 3	15	48	312.5	181.4 - 443.6	43.17	347.5	205.4 - 489.5	0.35	42,857.1	0 - 183176.8	772	194.3	96.7 – 291.7

NOTE: CI, Confidence Interval; n, number of contact events.

5.4 DISCUSSION

This is the first study to investigate the contact load and injury risk of professional Scottish Rugby Union match play. In section A of this study, a primary aim was to quantify the contact demands of match play for positional groups. It was hypothesised that Forwards would engage in considerably more contact events and have a much greater contact volume than Back positions. Indeed, Forwards were exposed to much higher contact demands than Backs in this study. An additional aim of section A was to investigate how these demands were related to pitch location and match quarter, and whether these influenced match injury risk. In the 2^{nd} half of match play, players had a higher contact volume and engaged in more contact events. Furthermore, players sustained more injuries during the 2^{nd} half of match play, which trended towards a significantly higher injury risk compared to the first half in this study. The final aim of section A in this study was to investigate the relative risk of injury from specific contact related factors in Rugby Union match play. Given the considerable number of injuries for Ball Carrying in this study, the relative risk of injury was investigated for these events. It was hypothesised that specific tackle-related risk factors would significantly increase injury risk, and that these would differ between Forwards and Backs. This was confirmed in the present study, and is further discussed in the discussion.

For section B of this study, a primary aim was to compare the incidence of injury from various workload types often used in studies monitoring workload and injury risk (volume, GPS data and video coding data). It was hypothesised that positional differences would exist, and this would be influenced by the workload measure being investigated for injury incidence data. The various measures adopted in this study, and the positional differences reported, both when using the same workload measures and different workload measures are discussed in section 5.4.6.

5.4.1 Main Findings (Section A)

As hypothesised from the literature, Forwards engaged in more contact events, and accordingly had a higher contact volume than Back positions in this study. Second Row players had the greatest mean match volume per player per match for Forwards (1.17 hours). These players also had the highest mean contact volume and mean contact events per match over any other positional group (3.07 minutes and 48.1 contact events per match, respectively). Hookers had the lowest mean match volume per player per match (0.78 hours), and also reported the lowest mean contact volume per player per match (2.09 minutes). Props were subjected to the lowest mean contact events per player per match for Forwards (36.3 contact events). When investigating Ball Carrying and Tackling only, Back Row players had the greatest mean contact volume per player per match for Forwards (24.3 seconds), whereas Props had the lowest (14.07 seconds). Similarly, Back Row players were involved in the highest mean contact events for Ball Carrying and Tacking per match (17.8 contact events), and Props were involved in the lowest mean contact events per match (10.7 contact events). Centres had the highest mean match volume for Backs (1.21 hours per player per match), closely followed by Back 3 players (1.20 hours per player per match). Scrum Half players had the lowest mean match volume per player per match (0.8 hours). Centres reported the highest mean contact volume per player per match (0.60 minutes) and the highest mean contact events per match (23.5 contact events). Stand Off players had the highest mean contact volume and mean contact events for Ball Carrying and Tackling (18.58 seconds and 15.3 contact events per player per match, respectively). Scrum Half players had the lowest volume and contact events for all categories.

Ball Carrying was clearly reported as the highest injury risk event out of all contact events (79.8 contact events per injury) in this study. As such, the relative risk of injury for Ball Carrying was assessed for each coding category. From the findings reported in this study, Backs were significantly more likely to be injured when approaching the tackle at a fast velocity (RR = 9.83, 95% CI 2.14 – 45.11, p=0.003), or when T1 approached the tackle at a fast velocity (RR = 2.71, 95% CI 0.69 – 10.72, p=0.155). Forwards were significantly more likely to be injured when approaching T2 at a fast velocity (RR = 10.86, 95% CI 1.57 – 75.26, p=0.029), or when T2 approached the tackle at a fast velocity (RR = 22.46, 95% CI 3.35 – 150.43, p=0.001). Back were significantly more likely to be injured when running behind (RR = 4.62, 95% CI 1.04 – 20.43, p=0.044), whereas Forwards were had a significantly higher injury risk when hit side-on (RR = 4.65, 95% CI 1.26 – 17.16, p=0.021). Forwards reported a high RR for high impact tackles, but this was not significant (RR = 3.49, 95% CI 0.95 – 12.87, p=0.060). Forwards did however, report a significantly lower injury risk for tackles compared to collisions and off the ball (OTB) tackles (RR = 0.04, 95% CI 0.01 – 0.18, p=0.000). Collisions and OTB tackles also significantly increased injury risk for Forwards compared to tackles (RR = 12.99, 95% CI 1.81 – 93.35, p=0.011; RR = 58.88, 95% CI 12.52 – 276.88, p=0.000, respectively). There was not enough data to provide the injury risk of collisions and OTB tackles for Backs. Forwards had a significantly higher injury risk when knocked laterally following the tackle against T1 (RR = 5.71, 95% CI 1.46 – 22.38, p=0.012). Forwards were significantly more likely to be injured when they ‘lost’ the tackle contest against T2 (i.e., were hit negatively), or when T2 continued in a positive direction (RR = 9.24, 95% CI 1.33 – 64.17, p=0.024; RR = 12.20, 95% CI 1.28 – 116.12, p=0.029).

For match quarter, the relative risk of injury was significantly greater in the 3rd quarter of match play (RR = 2.14, 95% CI 1.06 – 4.33, p=0.034). There was also a trend for injury risk to be significantly greater in the 2nd half of match play compared to the 1st half (RR = 2.06, 95% CI 0.98 – 4.35, p=0.057). Players were exposed to a higher contact volume and engaged in more contact events in the 2nd half of match play compared to the 1st half (2nd and 1st half mean contact volume = 20.33 and 18.62 minutes, respectively; 2nd and 1st half mean contact events = 387 and 359.2 contact events per match, respectively).

5.4.2 Main Findings (Section B)

All Back positions other than Scrum Half players covered greater total distances during match play compared to Forward positions. All Forwards engaged in a higher number of contact events than Back positions. Match injury incidence rates were highest for Hookers out of any other Forward position. Hookers also had one of the lowest match distances covered and had a lower contact exposure than both Second and Back Row players. Hookers did, however, engage in the greatest number of contact events per 1000 meters covered. This may reflect a high relative match demand for these players.

Similar to Hookers, Centre and Back 3 players reported the highest injury incidence rates for Backs and also reported the highest number of contacts per 1000 meters. A noteworthy point was the high incidence rates for Back 3 players given the lack of evidence suggest a high contact load for positional group. As per section A, a large portion of time loss injuries were occurred to Back 3 players, and this likely reflects the nature of the contact events Back 3 players are exposed to (e.g., velocity on approach to the contact event), rather than the number of contacts or volume of contact exposure.

An important point of consideration in this study was the incidence values reported depending on the loading measure used and the method adopted to report incidence data. Using the method of 15 (players) multiplied by 80 (minutes) resulted in Props, Back Row players, Stand Offs and Centres all reporting the same match injury incidence values (250 injuries per 1000 hours). When reported from the GPS data however, these were much more individualised based on the exact match time of each player. Furthermore, the incidence rates for contact volume were very high compared to overall match times, which reflects the risk of injury from contact events in Rugby Union – particularly for Back positions in this study. Importantly, all Back players were involved in less contact events and thus reported a lower contact volume compared to Forwards. This may highlight that Back positions are more often involved in contact events that have a higher risk of injury (e.g., velocity is a clear risk factor for injury in this study, and Back players have more space and a greater opportunity to increase velocity prior to the tackle).

5.4.3 Contact Volume and Events for Positional Groups (Section A)

The demands associated with varying positional groups in elite Rugby Union can be large, and highlight that training strategies for match preparedness cannot be achieved via a "one size fits all" approach. For instance, in this study Second Row players were involved in the highest mean contact volume per match, and reported the highest mean contact events per match out of any other positional group, yet reported the lowest number of injuries for Forward positions. Such a large exposure to contact events with such a small injury risk suggests that Second Row players are highly resilient to contact related fatigue and an increased injury risk. However, these finding also suggest that other factors (beyond contact events/contact volume engaged in) may play a larger role when investigating injury risk in professional Rugby Union match play.

It is difficult to fully understand what aspects of Rugby Union match play are directly linked to injury and what aspects are not. For instance, Back Row players reported the greatest number of identified injuries from video coding compared to other Forwards positions. In addition, Back Row players also reported the greatest mean contact volume and mean contact events per match for Ball Carrying and Tackling events. Given the high risk of injury associated with Ball Carrying and Tackling events in this study, these findings indicate that rather than total events engaged in, it may be the type of contact events, and player exposure to these events that influence injury risk. Contrary to this theory however, both Stand Off and Centre players reported greater mean contact volume and mean contact events per match for Ball Carrying and Tackling compared to Back 3 players, yet Back 3 players reported the greatest number of time loss injuries from match play. These findings suggest two possible scenarios: 1). Forwards may be more susceptible to injury when engaging in a high proportion of Ball Carrying and Tackling events since these players already engage in more high-intensity static activity (i.e., as shown for Scrummaging, Mauling and Rucking in this study). As such these players may be more fatigued from contact work, and are thus at a higher injury risk of injury. Previously, Roberts *et al*. (2008), reported that, although Backs completed greater high-intensity running than Forwards, Forwards engaged in significantly more high-intensity static activity compared to Backs (7.93 minutes vs. 1.30 minutes, respectively, $p < 0.001$), Furthermore, in line with the findings from the current study, Roberts *et al*. (2008), also reported that this was due to Forwards engaging in more Scrummaging, Mauling, Rucking and performing more Tackles. Roberts *et al*. (2008), reported that Backs spent 58% of their match time in running related activities and 42% of their time in static (contact related) activities, whereas Forwards spent 13% of their time in running related activities and 87% of their time in static (contact related) activities. The authors previously suggested that match fatigue may be manifested through the amount of high-intensity activity performed by the players, but that high-intensity activity was unchanged throughout match play. Importantly, measuring fatigue was beyond the scope of this study, but these findings may provide evidence of the possible deteriorating effects of a high contact workload, and a higher susceptibility to injury for certain contact events; 2). Rather than the total number/volume of other contact events increasing injury risk for Ball Carrying and Tackling events, it is quite simply the nature of how high risk events (in this case Ball Carrying) develop from the pre-tackle phase through to the end of the tackle phase. Given the high risk associated with Ball Carrying in this study, a comprehensive evaluation of Ball Carrying risk factors in relation to injury risk was conducted (see the section below, 5.4.4). This was performed in order to investigate how injury risk may be influenced by more than just the volume and number of events a player engages in during Rugby Union match play.

5.4.4 The Relative Risk of Injury – Ball Carrying (Section A)

5.4.4.1 Ball Carrier and Tackler Velocity

A study previously conducted by Fuller *et al.* (2010), investigated injury risk factors associated with tackling in Rugby Union. The authors reported that a high velocity into the tackle was a significant risk factor for injury ($p < 0.01$) for both ball carriers and tacklers. In line with this finding, the present study reported that Backs were significantly more likely to be injured when approaching the tackle against T1 at a fast velocity, or when T1 approached the tackle at a high velocity. Similarly, Forwards were significantly more likely to be injured when approaching the tackle against T2 at a fast velocity, or when T2 approached the tackle at a fast velocity. Similar findings have previously been reported in senior Rugby Union clubs from Scottish

Rugby Union districts. Garraway *et al.* (1999), conducted a study investigating risk factors for injury during tackling events. The authors reported that in all injury events recorded in their study, the BC or tackler was either sprinting or running. Furthermore, Wilson *et al.* (1999), reported that approximately 70% of injuries were a result of players running into the tackle during Rugby Union match play. Beyond assessing all injuries, Montgomery *et al.* (2018), investigated the mechanisms of anterior-cruciate ligament (ACL) injuries in professional Rugby Union and reported that, although both a combination of high and low speeds resulted in ACL injury, the majority of these were a result of high speeds for Forwards and Backs. Similar to Montgomery *et al.* (2018), a recent study conducted by Cross *et al.* (2019), investigated specific tackle-based factors associated with concussion injury risk in professional Rugby Union. The authors reported that the most compelling finding from their study was that if the tackler accelerated into the tackle (Odds Ratio [OR] 2.49, 95% CI 1.70 - 3.64) or was moving at a high-speed (OR 2.64, 95% CI 1.92 - 3.63), there was a significant risk of sustaining a concussion injury. Cross *et al.* (2019), also suggested that being able to limit the speed of the tackler would be a very complex challenge but could reduce the risk of concussion the most out of any other risk factor investigated in their study. Similar to the present study (which investigated all time loss injuries), Cross *et al.* (2019), reported that when the tackler (T1) was travelling at a high speed, Backs sustained more injuries than Forwards. The aforementioned findings, which span over 2 decades and investigate all injuries and specific injury types all report the high risk of injury associated with running at high-speeds into the tackle. This finding highlights the importance of improving tackle technique and execution at higher speeds for players even at the professional level. . However, this requires further investigation, as the authors also reported this may have the opposite of the intended effect, such as tacklers accelerating into tackles more often – a high injury risk factor for concussion in their study (Cross *et al.*, 2019).

5.4.4.2 Movement Direction and Tackle Location

Within the present study, the RR of injury was significantly increased for Backs when the BC was running behind. Similarly, when Forwards were hit side-on, they were significantly more likely to be injured. Garraway *et al.* (1999), previously reported in SRU district teams that over 50% of injured players were tackled from behind or out-with the player peripheral vision. This may have been the case in the current study when Backs were running behind and Forwards were hit from a side-on angle. Indeed previous studies have reported similar findings. Burger *et al*. (2016), reported that Rugby Union Ball Carriers were less likely to be injured if they were aware of the tackler approaching from behind or from side-on, and that Ball Carriers were more likely to be injured if the tackle came from outside of their peripheral vision. Furthermore, Burger *et al.* (2017), reported that Ball Carriers were at a higher injury risk if they were unaware of the impending tackle during Rugby Union match play. An important point of consideration for all of these studies, however, is that non-professional players were included. Therefore, these non-professional players may have been less attune to their surroundings and lacked awareness of oncoming tackles (thereby increasing injury risk). Importantly, however, the findings in the current study suggest that a lack of tackle awareness, and consequently not being able to anticipate/brace for incoming contact, can influence injury risk regardless of the level of play. Within the present study, the majority of off the ball (OTB) injury events - which resulted in one of the highest injury risks - was associated with a complete lack of awareness of the impending tackle. If a player is unaware of the impending tackle, there is little to nothing that player can do to minimise the risk of injury at the moment of contact, regardless of ability or improvements in tackle technique. Therefore, being aware of your surroundings may be one of the most important injury aspects in Rugby Union match play, but this needs further research at the professional level. Contrary to these aforementioned findings, Wilson *et al.* (1999), reported that players were more likely to be injured when making front-on tackles, rather than from behind or the side. It is likely however, that in the last 2 decades, players have substainly improved their skill related tackling ability, and therefore are better able to get into the right position and make safer tackles when approaching the tackle from a front-on position.

5.4.4.3 Tackle Impact Force and Collision Events

There was a significant trend towards a greater injury risk for high impact tackles compared to low and moderate impacts for Forwards in this study. In addition, tackling was associated with a significantly lower prosperity to cause injury compared to OTB and collision events. Tackles resulted in the greatest number of injuries in this study, simply through the sheer number of these events. However OTB and collision events resulted in the greatest propensity to cause injury. Similar findings were also reported by Fuller *et al.* (2010). The authors reported that tackles resulted in the greatest number of injuries simply through the number of times these events were engaged in, but that high impact force and collision events were both identified as significant injury risk factors in the professional game. The authors reported that minimising high impact tackles, and conducting research into the nature and biomechanics of these events would be one of the most efficient methods for reducing injury risk when engaging in tackles. However, authors also noted that at the professional level, avoiding such events is difficult. Indeed, it is a professional Rugby player's job to perform and succeed at the highest level of Rugby Union match play. Therefore, a player must stop an opponent and actively contest for ball possession whenever necessary. Thus, without drastically changing the laws of the game it may not be possible to prevent such occurrences. Future research may have a greater impact in minimising injury risk by understanding what aspects of these high impact events are more associated with injury, rather than trying to get players to actively avoid them. One method may simply be to attempt a low-impact fend that does not increase impact force. For instance, when the BC attempted a moderate or strong hand off in this study, the risk of injury was much lower than that compared to a moderate or strong bosh/bump. Thus, using an arm to actively slow or push the tackler away may be more effective at minimising injury in Rugby Union, which has previously been reported by Burger *et al.* (2017). Future research would be needed over a much longer time span however to confirm if such tactics would work in reducing high impact injuries at the professional level.

5.4.5 Pitch Location and Game Quarter (Section A)

The playing strategy in this study, in terms of contact volume and events in relation to pitch location reflected that of Fuller *et al*. (2007a). Ball carrying events were lowest in the team's own 22m area, which likely reflects players' decision to kick towards centre-field or into touch, thereby clearing any immediate threat and providing an opportunity to move up the field and retain possession of the ball (Fuller *et al*., 2007a). Tackling events on the other hand were highest in each team's own half/own 22m area. Indeed, these locations – particularly inside the 22m area – are associated with more defensive play, where players must prevent the opposition moving closer towards the goal line. Similar to Fuller *et al*. (2007a), the majority of contact events, (BC, Tackling, rucking and scrummaging) were performed most often within centre-field, which may highlight a higher overall loading in these pitch locations (22 – 50m and 50 – 22m areas). Nevertheless, the highest proportion of mauls occurred in the opposition's 22m area, of which nearly all of these were following a lineout. This finding suggests that a clear tactic for teams when inside their opposition's 22m area is to kick to touch when receiving a penalty. This allows the team to move closer to the opposition's goal line whilst retaining possession of the ball. Players can then perform an attacking maul to drive over the opposition's goal line. A similar finding was previously reported over a decade ago by Fuller *et al.* (2007a), and clearly still remains a well utilised tactic in the professional game today.

Similar to findings reported by Fuller *et al.* (2007a), there was a higher number of contact events (and a high contact volume) in the 4th quarter of match play in this study compared to the previous quarters. In line with these findings, a more recent study conducted by Tierney *et al.* (2018), in elite level Rugby Union reported that significantly more tackles occurred during the 4th quarter of match play compared to the 1st and 2nd quarter. Tierney *et al.* (2018), suggested that more tackles occurring in the final quarter of match play provides an explanation for the high number of tackle-related injuries that occurred in the final quarter. Furthermore, Fuller *et al.* (2007a), reported that a greater number of contact events in the final quarter of match play is likely not associated with an increased intensity of play or a change in the nature of play, but simply a result of added time allowed by referees towards the end of the 4th quarter (Fuller *et al*., 2007a), thereby increasing the number of contact events in this final quarter. Fuller *et al.* (2007a), however, also suggested this for the 2nd quarter of match play (i.e., prior to the half time whistle). In the present study, there was a linear association between game quarter and mean contact volume per match (i.e., mean match volume increased as players entered each new match quarter). Furthermore, the mean contact events per match was lowest in the 2nd quarter of match play in this study (177.8 contact events), and highest in the 3rd and 4th quarters of match play (183.7 and 203.3 contact events, respectively). This finding suggests that as players' progress through the match, they are at an increased injury risk through a greater number of contact events per quarter, and consequently, a higher risk of injury due greater contact related fatigue.

In the current study, the relative risk of injury was significantly higher in the 3rd quarter of match play compared to the other match quarters (RR = 2.14, 95% CI 1.06 – 4.33, p=0.034). Similarly, Bathgate *et al*. (2002), also reported that the majority of injuries occurred in the third quarter of match play in elite Australian Rugby Union players. The authors suggested that this may have been a result the new substitution law introduced in 1996, allowing uninjured players to be substituted into the game. Therefore, if a player knew they were going to be substituted in the 3rd quarter, they may have played at a greater intensity in an effort to make an impact. However, no differences were reported in injury rates pre and post this substitution law (Bathgate *et al*., 2002). A second reasoning for the higher injury rates in the 3rd quarter may have been a result of reduced focus and concentration due to the half time break, or an inadequate warm up not preparing players for the in-game demands (Bathgate *et al*., 2002).

Unfortunately these were not investigated in the present study, therefore the higher injury rates in the third quarter may be due to psychological factors such focus and concentration or simply a dip in the readiness of players to withstand the match demands if the warm up is not sufficient. Alternatively, it may simply be that players have not fully recovered from the 1st half of match play and enter the 2nd half at a much higher intensity following the half time break. However, this is speculation as there was no investigation into the preparation of play prior to the third quarter of match play, nor any measure of match fatigue following the first half of match play to provide any evidence for these theories.

Within the present study, the 2nd half of match play reported a higher relative risk of injury compared to the 1st half (RR = 2.06, 95% CI 0.98 – 4.35, p=0.057). Although assessing fatigue was beyond the scope of this study, this finding may indicate that as players' transition through match play injury risk is increased - at least to some degree - as fatigue sets in. Similar findings have previously been reported in South African Youth Rugby Union players. Burger *et al.* (2017), investigated the mechanisms and factors associated with tackle injuries in Rugby Union, and reported that, compared to the 1st quarter, injury risk was significantly greater in the 3rd (relative risk ratio [RRR] = 9.75 [95% CI 1.71 - 55.64, p=0.010) and 4th quarters for Ball Carriers (RRR = 6.97, 95% CI 1.09 - 44.57, p=0.040). The authors concluded that this greater injury risk may be attributed to a heightened level of fatigue due to the repetitive nature of contestable contact scenarios in Rugby Union match play. Indeed, this would suggest that as players perform more and more tackles, the level of fatigue increases, which may ultimately deteriorate the stress-bearing capacity of musculoskeletal soft tissue. Therefore, the structural integrity of the muscle and surrounding soft tissue is compromised, resulting in a higher injury risk when subjected to force loads via contact (Kumar, 2001; Cross, *et al.*, 2017). In line with this, it has previously been reported that there is a positive linear relationship between the number of tackles (made or received) in Rugby Union and the level of muscle damage sustained (via increases in blood creatine kinase activity in this instance) (Takarada, 2003). This increased muscle damage is likely to hinder a player's ability to adequately contest against the opposition during the contact events, particularly towards the end of the game (Burger *et al.*, 2017; Hendricks & Lambert, 2010). Furthermore, match related fatigue has also been shown to decrease a player's level of technical ability to perform efficiently in the tackle contest (Gabbett, 2016b), which may thereby increase injury risk through entering the tackle in a high risk position (e.g., having their head on the wrong side of the tackle).

Indeed, Gabbett, (2016b), previously investigated the influence of fatigue (via repeated high-intensity efforts, RHIEs) on tackling ability in Rugby League players. The authors reported that following each cycle of RHIEs, players' ability to tackle was progressively reduced, with a moderate reduction in tackling ability following the 4^{th} RHIE (Gabbett, 2016b). Such findings may translate to the latter stages of match play, such that, as players engage in more and more contact events, their ability to contest and adequately maintain efficient technique is reduced, resulting in a higher injury risk. Interestingly, Gabbett, (2016b), also reported that players could counteract this drop in technical ability with greater relative lower body strength (4 rep max squat/kg); players with the greatest lower body strength were the most efficient at maintaining their tackling ability whilst in a fatigued state. Given the lengthy contact volume of single scrummaging and mauling events (6.21 [± 2.95] and 9.63 [± 5.97] seconds) performed by Forwards, such knowledge may be very important for these players.

A limitation of previous studies investigating Rugby Union (or League) contact load and injury risk is that players have not been separated into any type of positional groupings. This is important as the contact differences between positional groups in Rugby Union are large. For instance, Reardon *et al.* (2017b), previously reported that even during the worst case scenario in elite Rugby Union match play (longest periods of gameplay in relation to locomotion and collision demands), tight Five (Props, Hookers and Locks) and Back Row Forwards engaged in significantly more collisions than both Inside and Outside Backs during WCSs (0.73 & 0.89 collisions·min^{-1} vs 0.28 & 0.41 collisions·min^{-1}, respectively). Back positions on the other hand, reported greater total distances (318 m vs 289 m) and high-speed running distances (11.1 m·min^{-1} vs 5.5 m·min^{-1}) – a finding previously reported in Chapter 4B. In the present study, Backs also covered greater mean distances (other than Scrum Halves) and were subjected to much lower mean contact events per game than Forwards. Such findings extend beyond Rugby Union, and have been reported in recent a Rugby League meta-analysis also (Naughton *et al.*, 2020).

5.4.6 A Comparison of Methods for Investigating Match Load and Injury Risk (Section B)

Similar to previous findings, Back positions covered greater total distances during match play, whereas Forwards engaged in considerably more contact events (Section B) (Cunniffe *et al.*, 2009; Cunningham *et al.*, 2018; Pollard *et al.*, 2018; Reardon *et al.*, 2017b). These two measures of match load (distance vs. contact events) showcase a very different type of load undertaken by the two distinguishable positional groups in this study. Nevertheless, the influence of this data on injury can still be difficult to comprehend. For instance, Hookers reported the highest match injury incidence rates out of all Forward positions, yet had one of the lowest mean match distances, and were subjected to comparatively low contacts compared to Back Row and Second Row players. Such data suggests that other factors come into play when investigating Rugby Union injury risk. Interestingly, Hookers did report the greatest number of contacts per 1000 metres covered. This relative match intensity metric may therefore highlight the importance of combining commonly used loading tools for understanding the demands of match play in relation to injury likelihood. In line with this, both Centres and Back 3 players had the highest contacts per 1000 meters for Back positions, and both positional groups reported the highest injury incidence rates for Backs. These findings provide a potentially more accurate measure of load by investigating the contact demands in relation to locomotive data, and this metric can also be used in relation to any other GPS/IMU variable (e.g., contacts per 1000m of high-speed running or PlayerLoad^{TM} arbitrary units etc.). Although investigating this measure in relation to injury is beyond the scope of the current paper, this could be an important avenue for future research. Noteworthy, was the very high incidence rates for Back 3 players. There is no loading data to suggest that these players were exposed to higher loads than any other positions, yet these players reported the highest injury incidence values out of any other positional group. This finding likely reflects the extent of how the nature of each contact event can influence injury risk, rather than the overall load of match play. For instance, from Results Section A, the RR of injury was significant for Back players approaching the first tackler at a fast velocity, and this has been reported in previous Rugby Union research assessing match injury risk (Cross *et al.*, 2019; Fuller *et al.*, 2010). Back 3 players have one of, if not the most amount of space to build up momentum prior to contact. Therefore, there may be clear risks associated with these players that are difficult to prevent in the modern game.

Depending on the methodological approach adopted to investigate injury data in professional Rugby Union, the results reported will vary considerably. Previous methods have used simple calculations of match volume by multiplying the number of matches played (usually in a season) by the number of players exposed (15 players), by the duration of the match (80 minutes) (Falkenmire *et al*., 2020; Gabbett *et al.*, 2011; Palmer-Green *et al*., 2015; West *et al*., 2020). Indeed, this may provide a simple measure of match volume, but it is not as accurate or as individualised as taking the GPS data for each individual player (where possible); the injury incidence rates may vary considerably, which paints an entirely different picture of what may be true. For instance, in this study Props, Back Row players, Stand Offs and Centres all had an injury incidence of 250 injuries per 1000 hours using the first method (15 x 80 minutes). However, when using the actual match volume via GPS devices for these players, injury incidence data varied considerably for these players. Another important method used in studies investigating Rugby Union match demands is the use of 'ball in play time' (BiP). Given that Rugby Union is an intermittent sport, in which the BiP time is usually less than ball out of play time (Pollard *et al.*, 2018), assessing the specific demands of BiP periods is important to truly understand the demands of the game. For instance, Pollard *et al.* (2018), reported that BiP workload metrics (meters covered per minute, high metabolic load per minute, high speed running per minute, collisions per minute) via GPS/IMU devices were significantly higher than whole match averages during international Rugby Union match play. Similar results have also been reported in earlier work (Reardon *et al*., 2017b). Given that the vast majority of Rugby Union injuries occur during BiP time, this is an important alternative for assessing match demands, which ties into the important use of match video coding when assessing in-play demands and injury risk. Unfortunately the use of BiP was beyond the scope of this paper, but these findings highlight that consideration of this method when investigating match load and injury risk is important.

Another method beyond whole match volume is the use of contact volume. Indeed, when looking at the contact volume, the injury incidence rates are extremely large in this study due to such a small proportion of the match involving contact. This method of assessing injury incidence, although unique to this study, highlights the reality of contact injury risk in professional Rugby Union match play. Interestingly, when monitoring the injury data via per 10,000 contact events, this highlights the high risk for Back players - these players are subjected to considerably less contact events yet reported injury incidence values much greater than Forwards. Similar findings have previously been reported in Rugby League by Gabbett *et al.* (2011). The authors split players into Hit-up Forwards (props), Wide Running Forwards (Second Row and Lock), Adjustables (Hooker, Halfback, Five-eighth and Fullback), and Outside Backs (Centre and Wing). Although authors highlighted that Hit-up Forwards and Wide Running Forwards reportedly perform more collisions than Adjustables and Outside Backs, the authors reported that Adjustables and Outside Backs had the highest incidence of injury per 10,000 contact events. Furthermore, Wide Running Forwards had a significantly lower incidence of injury (per 10,000 contact events) than both Adjustables and Outside Backs.

The findings from the present study and those reported by Gabbett *et al.* (2011), may further support the notion that it is the nature of the contact event that influences injury the most, rather than the overall loading of multiple events. Therefore, a few tackles that involve multiple risk factors (e.g., high velocity, large impact, hit from behind…) may be much more dangerous to injury likelihood than many tackles involving few injury risk factors (e.g., low velocity, lower impact, hit front on…). Indeed, Second Row players reported the highest mean match distance for Forwards and the highest mean contact events per match overall yet reported the lowest injury incidence rate out of every position. Scrum Half players, on the other hand, had the lowest match loads, yet one of the highest injury incidence values per 10,000 contacts. These findings further highlight the need to understand what aspects match load, from volume to locomotive data, through to contact work that actually result in a higher injury risk. It appears - at least from the current study - that specific contact risk factors such as velocity, tackle type (i.e., collisions) and tackle location may be more associated with injury than total contact volume and/or number of contact events engaged in.

5.4.7 Limitations and Methodological Considerations

There are a number of limitations that need to be considered in this study. Firstly, only 12 games throughout a season of three professional teams were used in the analysis. Indeed, the findings of this study therefore may reflect the characteristics of those 12 games selected, rather than the loads and injury risks associated with an entire season of professional Rugby Union. Nevertheless, the results of this study still support those over multiple seasons (Cross *et al.*, 2019; Fuller *et al.*, 2010). A second limitation of this study was the lack of injury data for identified injury events. Due to a lack of injury data, the RR of other events beyond Ball Carrying could not accurately be investigated in this study, nor could the full RR for all Ball Carrying events truly be explored for Forwards and Backs. On this basis, future research is recommended to use the same metrics in this study over a much longer time frame to further explore the risks associated with contact events in Rugby Union, and to cross examine the results presented in this study for elite Scottish Rugby Union players. Only match data was included in this study. Therefore the results cannot be extended to training or the overall contact load a player may have been exposed to in a given week. There was also no measure of physical fatigue or psychological factors included in this study. Therefore, the influence of these factors on the injury data presented in this study could not be explored.

5.4.8 Conclusion

This study aimed to investigate the contact demands and injury risk of positional groups in elite Scottish Rugby Union players. It was hypothesised from previous literature that specific contact categories would increase injury risk for players entering the tackle phase, and this was confirmed in the current study, particularly for velocity and impact data - finding previously reported in a similar cohort of professional Rugby Union players. Other risk factors considered were the influence of total contact volume and number of contact events on injury. Results from the current investigation, however, suggest that it is not number of impacts or total contact volume that influence injury risk the most, but how each contact event unfolds. Indeed, certain characteristics are clearly associated with injury in Rugby Union and future research should focus on alternative methods to minimise these high-risk aspects of the tackle. Depending on the methodological approach used to track and monitor player load and injury, the 'loading picture' may look very different for all players, and for positional groups. Combining commonly used loading metrics to create more simplified, yet multifaceted loading tools such as events per 1000m may be more appropriate, but this requires further research. A final point of consideration is the high injury risk revealed for contact events at the professional level in this study. The researcher recommends that practitioners and researchers alike use the findings from this study to further investigate methods to minimise the injury risk and improve player welfare. Ball carrying events appear to be one of highest risks for injury, and positional differences are also evident. This study therefore further highlights the need for positional assessments for load and injury, rather than a "one size fits all" approach. Indeed, the relative player match loads vary considerably from position to position in elite Rugby Union, and the impact of such load on injury risk are difficult to currently comprehend without further investigation. Studies incorporating over multiple seasons, utilising multiple teams, and splitting players for positional analysis are recommended in the future.

CHAPTER 6: GENERAL DISCUSSION AND CONCLUSION

6.1 INTRODUCTION

The overarching aim of this thesis was to investigate some of the key approaches used to monitor training and match loads in elite Scottish Rugby Union, and assess how these loads are associated with injury risk. To achieve this overarching aim, Chapter 3 aimed to investigate the influence that training volume and match exposure have on training and match injury risk; Chapter 4B aimed to investigate the influence of pitch-based training and match workload via GPS and IMUs, and the influence these workloads have on injury risk; Chapter 5 aimed to investigate the contact based workload of Rugby Union match play and how contact exposure can influence injury risk in elite Rugby Union players. In turn, this thesis aimed to provide practical strategies for reducing injury risk in elite Rugby Union.

A number of research questions were also developed to achieve this overarching aim. A summary of findings from chapters 3 – 5 are provided in the following section (6.2 Summary of Findings). This chapter showcases how the aims and subsequent novel findings presented in this thesis contribute to the current research area. Considerations regarding the methodological approaches adopted are discussed and further explored. The researcher provides a number of key practical applications that have emerged from this thesis. Finally, the potential impact of the current research in relation to load monitoring strategies and injury risk are provided, along with gaps that still exist in this field of study. Directions for future research are discussed following the outcomes of this thesis.

6.2 SUMMARY OF FINDINGS

In elite Rugby Union, players are exposed to various training and match loads on a daily, weekly, monthly and yearly basis. Understanding how these varying loads relate to player injury risk is fundamental for both success within the sport and player welfare. There is an abundance of literature supporting the utility of monitoring training and match loads in Rugby Union to further understand the demands and injury risk of the sport, particularly at the professional level. These studies have helped quantify the relationship between training and match loads and their impact on performance and injury risk. In turn, this data has been used to develop more appropriate training strategies that optimise player development and improve player welfare. A comprehensive evaluation of the literature in chapter 2 identified a number of areas that lack supporting evidence or simply have not been addressed. There is little supporting evidence to highlight how external workload has influenced injury risk in elite Rugby Union, and therefore, a lack of information on strategies that can be adopted by teams to minimise injury risk associated with the sport. With this in mind, an overarching aim of this thesis was to conduct a novel investigation into the utility of some of the most common methods employed to monitor Rugby Union workload and their association with injury risk. This underpinned the aims, objectives, and ultimately the research questions of chapters 3 - 5. The key findings in relation to the research questions developed in this thesis are summarised below:

i. **Chapter 3 - How does training and match volume and exposure influence injury risk in elite Scottish Rugby Union players?**

Key Findings:

Players who averaged ~ 7 hours per week of training over the 2-season analysis had the lowest injury incidence and burden rates compared to players with lower training volumes. Players with very high 1- and 2-weekly cumulative training volumes (> 9.61 and 17.66 hours, respectively) had a significantly higher injury risk compared to the reference group. Players with a 'high' training volume had no association with injury risk for any cumulative trained period, suggesting that appropriately high training volumes over 1-4 weekly periods may reduce injury risk. When players were exposed to training volumes above what they were previously prepared for (i.e., a daily ACWR value > 1), injury risk linearly increased as the ACWR increased (this was for daily rolling and EWMA methods). Players who were exposed to less than 15 matches per season had the highest injury incidence rates, whereas players who were exposed to > 25 matches in a season had the lowest injury incidence rates. Match burden was considerably reduced for players involved in ≥ 20 matches per season.

ii. **Chapter 4A - Can two different GPS devices from different manufacturers reliably measure the total distance covered by Rugby Union players during pitch-based training?**

Key Findings:

There was good interunit reliability between the Catapult and GPSports units used in this study (coefficient of variation = 1.8%). In addition, the intra-class correlations (ICC) between devices to report total distance (TD) were strong (ICC > 0.9). Following the construction of Bland-Altman limits of agreement plots, total distance was reported to be consistently higher for the Catapult S5 devices compared to the GPSport EVO units, resulting in a bias of 113.4m (a difference of 2.8 % between units, due to Catapult units reporting a higher distance). The maximum limits of acceptable agreement were 3.2 – 8.7%. Therefore, devices were reported to be reliable for reporting total distance. When players covered greater distances during training (> 4000 m), the difference reported between units was lower, suggesting more running related training activities improved interunit reliability. Finally, there was no proportional bias between units for measuring total distance (assessed via linear regression).

iii. **Chapters 3 and 4B - What load measures (i.e., daily loads, cumulative loads, weekly changes in load and ACWR calculated loads) are best for informing injury risk in elite Rugby Union, from both a volume (hours) and locomotive workload (GPS and IMU derived measures) perspective?**

Key Findings:

When investigating various ACWR methods, chapter 3 reported no association between weekly rolling (coupled and uncoupled) data and injury risk for training volume. This may highlight the lack of sensitivity for these weekly measures compared to daily ACWR methods (both rolling and EWMA) when investigating training volume (linear increase in injury risk as described above for daily methods).

For training volume, very-high 1- and 2-weekly cumulative loads significantly increased injury risk, whereas 3- and 4-weekly cumulative training volumes did not. This may highlight the increased risk of subjecting players to high training volumes over short periods of time.

Although there was a lack of significant findings for the training and match GPS/IMU intensity measures, there are potential areas of interest for future research. Increases in PlayerLoad^{TM}, meters > 80% maximum velocity and changes in weekly TD all reported higher a higher odds of injury. Furthermore, an intermediate ACWR for acceleration meters > 2 m·s^{-2} and a low ACWR for HSR meters when in a low chronic workload state significantly reduced injury risk.

iv. Chapter 5 - What are the contact demands and injury risk of elite Scottish Rugby Union, and how does this data compare to other well established loading monitoring practices?

Key Findings:

For both contact volume and contact events per match, Second Row players had the highest out of any other positional group (3.07 [± 1.74] minutes per player and 48.1 [± 26.9]) contact events per player). Props and Hookers reported the lowest for both contact volume and contact events per match for Forward positions (2.26 [± 1.05] and 2.09 [± 1.26] minutes per player and 36.3 [± 16.0] and 37.3 [± 20.6] contact events per player, respectively). For Back Positions, Centre and Stand Off players reported the highest contact volume (18.07 [± 11.53] and 18.58 [± 6.27] seconds, respectively) and number of events (23.5 [± 13.9] and 20.5 [± 3.4] contact events, respectively). Scrum Halves were involved in the lowest contact volume and number of contact events per match out of any positional group (8.10 [± 5.83] seconds and 9.0 [± 5.2] contact events per player). For Ball Carrying and Tackling events only, Centres and Stand Off players were similar to both Props and Hookers for contact volume and number of contact events per match.

During the 3rd quarter of match play, the RR of injury was significantly increased (RR = 2.14, 95% CI 1.06 – 4.33, p=0.034). The 2nd half of match play reported a greater injury risk compared to the 1st half but this was not significant (RR = 2.06, 95% CI 0.98 – 4.35, p=0.057). In addition, players engaged in approximately 1.7 minutes more contact volume and were involved in approximately 28 more contact events in the 2nd half compared to the 1st half of match play.

A fast velocity into the tackle was a significant risk factor for injury for both Backs and Forwards. This was the case when either the Ball Carrier or Tackler approached the tackle at a fast velocity. Importantly however, Backs were significantly more likely to be injured for T1 tackles, whereas Forwards were significantly more likely to be injured for T2 tackles. Tackles were associated with a significantly reduced injury risk for Ball Carriers compared to collisions and OTB tackle events. For collisions, this was a result of both a high impact force and a lack of tackle skill execution. For tackling events however (i.e., players wrapped their arms around the Ball Carrier), a high impact force still trended towards a significant increase in injury risk (RR = 3.49, 95% CI 0.95 – 12.87, p=0.060). For OTB tackles, this was often associated with a total lack of awareness of the incoming tackle (i.e., the Ball Carrier had recent released the ball and was thus not bracing or expecting the tackle). There was not enough data to provide the injury risk of collisions and OTB tackles for Backs alone. When Forwards were hit side-on, and/or knocked laterally against T1 they were significantly more likely to be injured. Forwards were also significantly more likely to be injured with they were knocked negatively and/or if T2 continued in a positive direction during the tackle contest.

6.3 CONTRIBUTION OF FINDINGS TO THE EXISTING LITERAUTRE

The findings presented in this thesis have made an original contribution to the rapidly evolving field of player load monitoring in team sport. The influence of various load monitoring practices on injury risk in elite Rugby Union have been explored by considering current knowledge and research practices, and adhering to recommendations regarding study design, statistical considerations and technological advancements. Considerations regarding the significance of this work in relation to the data numbers used in this thesis, particularly for Chapters 4B and 5 (see section 6.4) must be taken into account. Nevertheless, there are still a number of contributions, and these are outlined below:

- Providing the first study to investigate the influence of fundamental player load metrics (i.e., training and match frequency, volume and intensity) in elite Scottish Rugby Union teams in relation to injury risk.
- Reinforcing previous evidence on the training and match patterns of volume and exposure in elite Rugby Union teams, and how these patterns can influence injury risk.
- Reinforcing the importance of using multivariable analysis when investigating injury risk factors in elite team contact sports.
- Providing the first study to investigate training volume via multiple workload calculations and the utility of various acute: chronic workload ratios for assessing injury risk in elite Rugby Union.
- Reinforcing the reliability of GPS systems to measure total distance during Rugby Union pitch-based work

- Providing the first study in elite Rugby Union to investigate the running demands (via GPS devices housing IMUs) of elite Rugby Union training and match play, and how these demands influence injury risk.
- Outlining substantial positional differences in locomotive and contact work performed by Rugby Union players in match play (achieved via GPS devices with IMUs and video coding analysis methods, GPS and IMU positional differences provided in Supplementary Tables 2-11).
- Reinforcing previous evidence that has reported specific risk factors for Ball Carriers during Rugby Union match play.
- Demonstrating the utility of video coding analysis when assessing player loads and injury risk in Rugby Union.

6.4 CONSIDERATIONS OF THE METHODOLOGICAL APPROACH

The studies presented in this thesis were discussed in depth, and fully supported by the Scottish Rugby Union. This improved compliance when recording and sharing the workload and medical data across the teams used in this thesis. As a result, a comprehensive investigation of various training and match loads in relation to injury risk could be completed. On collection and storage of this data, the researcher remained consistent with approaches previously used in Rugby Union injury surveillance studies by adopting the methodologies recommended by the previous Rugby Union consensus statement (Fuller *et al*., 2007b). This meant that the data presented in this thesis could be compared to previous research investigating injury risk in elite Rugby Union, in turn, reinforcing previous observations and providing new avenues in which research is currently lacking. The methodological approaches adopted across the studies used in this thesis were largely influenced by previous literature investigating load and injury risk in elite Rugby Union cohorts, but there are still considerations that need addressed.

The inclusion of return to play (RTP) data beyond the point of injury (i.e., through the rehabilitation process until the player was deemed available for match selection) is likely to have to contributed to towards a lower volume (chapter 3) and GPS/IMU workload (chapter 4B) being linked to a greater injury risk. After sustaining a time loss injury there is likely to be a dramatic reduction in that players training and match volume (and consequently workload), therefore, if the injury is particularly severe, then weeks of low volume may be included in the analysis for that injured player. Nevertheless, injury and subsequent rehabilitation programmes are part of the injury process, and these lower volumes/workloads are already a result of sustaining a time-loss injury. In addition, for ACWR specifically, non-training weeks were excluded to minimise the possibility of very low ACWRs (0s) being linked to injury. It may be worth future research presenting the differences in injury data when RTP data is both included and excluded to fully understand the influence the inclusion of this data has on the reported findings.

With regards to the ACWR data presented in this thesis, there are also considerations with the use of ratios to investigate injury risk. For training volume (Chapter 3), there was no association between weekly coupled or uncoupled ACWRs and injury risk, whereas daily ACWR data was highly associated with injury, particularly for EWMA ACWRs. The locomotive workload intensity data (chapter 4B), on the other hand, reported a significant association for uncoupled weekly data in this thesis. This may suggest that variations in workload intensity from training and match play is more sensitive than variations in training volume data when investigating injury risk in Rugby Union. Nevertheless, regardless of the approach used or the findings reported, there have been warranted concerns for the inclusion of ACWR data in load monitoring studies (Impellizzeri *et al*., 2019; Lolli *et al*., 2017, 2019; Wang *et al.*, 2019). Previously, Lolli *et al.* (2019), reported a large and inverse within-subject correlation between the numerator (acute load) and its chronic load denominator, resulting in biased low acute loads when the chronic load was high (and vice versa). Impellizzeri *et al.* (2020), also expressed a number of concerns regarding the ACWR ‘sweet spot’ of 0.8 – 1.3 (Gabbett, 2016a), regardless of the ACWR method used. Furthermore, Wang *et al*. (2019), reported concerns regarding the methods by which ACWRs are calculated, and that coupled loads are not supported due to the spurious correlations demonstrated with this method (Lolli *et al*., 2017; Wang *et al*., 2019).

The methods employed in this thesis however, add to an ever growing body of literature addressing the methods used to monitor training and match loads and injury risk. The ACWR in all its various forms are one of the most utilised approaches to measuring player loads and investigating injury risk in professional team contact sports. Therefore, despite the limitations and methodological challenges surrounding this measure, research into the various methods in which these ratios are often derived are important for athlete monitoring programmes.

Data discretisation was an approach used in this thesis for chapters 3 and 4B for investigating the training volume and training and match locomotive workload in relation to injury risk in elite Scottish Rugby Union players. This method for injury risk analysis involves transforming a continuous data into discrete categories (Carey *et al.*, 2018). For example, percentiles, z-scores, arbitrary bins and median splits may be used (Carey *et al.*, 2018). Limitations with such methods exist including: a loss of within-category variation; potential for bias when selecting the reference category; lower statistical power; and inflated false discovery rates (Carey *et al.*, 2018). These authors highlighted through a number of simulated datasets (U-shaped, Flat and S-Shaped) with sample sizes of 1000 and 5000 (to represent one season vs. multiple seasons) that data discretisation methods reported higher root mean square error, an increase in false discovery rates and a decrease in false rejection rates. Model accuracy was thus reported to be higher when using continuous data sets for analysis.

Carey *et al.* (2018), however also demonstrated that increasing the sample size (i.e., collecting data over multiple seasons) could reduce the error and variance for 1000 observations and 5000 observations. Therefore, when larger sample sizes are used, incorporating multiple teams and seasons can minimise error (Carey *et al.*, 2018). In line with this, an increased sample size in the studies conducted in this thesis would have increased the number of injury events, would are required for small to moderate associations between workload and injury risk (approximately 200 injured subjects are needed) (Bahr and Holme, 2003). In the present study, multiple seasons and teams were used where applicable, but the injury data in some cases simply may not have been great enough for injury risk factors to be reported without caution via methodological approaches employed. Furthermore, the methods adopted in the studies conducted for volume (chapter 3) and locomotive workloads (chapter 4B), were carried out in a such a manner so that comparisons could be made between the current findings and those reported by previous literature using the same or similar methods of data discretisation. Nevertheless, this does highlight an important consideration for future studies investigating workloads and injury risk in team sports.

In relation to the lack of data and the statistical methods employed, it must also be noted that a large number of hypotheses were tested simultaneously within each study (i.e., multiple comparisons) may have considerably inflated the type 1 error rate due to a higher statistical probability of incorrectly rejecting a true null hypothesis (Chen *et al.,* 2017). Although this can be reduced with a greater significant level *a*, such as 0.01 instead of 0.05 (as used in Chapter 4B), it must be accounted for (Chen *et al.,* 2017), as an adjusted significance level may not have entirely resolved the issue.

There were a large number of workload variables used within the present study, and therefore it may have been more appropriate to use variable reduction techniques such as a principal component analysis (PCA) to identify logical combinations of the workload measures used (Williams *et al.*, 2017). Although in Chapter 4B VIFs were investigated and used as a means of preventing multicollinearity between workload variables, the inclusion of a PCA would have been desirable to understand what variables contributed the largest amount of variation in injury risk, whilst still capturing how each workload variable has uniquely influenced injury (Williams *et al.*, 2017).

Within the cohorts used across this thesis, there were individual player characteristics that could have been included with the use of multivariable models to further understand how the workloads may have influenced injury risk. With the study models assessing one predictor variable at a time, the inclusion of covariates (e.g., anthropometric measures, playing experience, fitness level, playing position, recurrent/previous injury) would have accounted for the unique effects of certain player-specific aspects on injury risk (Gabbett and Domrow, 2005; Malone *et al*., 2017c; Esmaeili *et al*., 2018), if multivariable models were used instead. Indeed, there are aspects of multivariate models that can control for certain effects, for example, a player returning from an injury will have high ACWRs when they return to full training, thus, due to their recent injury, increases in injury risk may be heightened, rather than due to a high ACWR. A second important point would have been the inclusion of more advanced statistical modelling techniques to account for repeated measures within the data and clustering. For example, clustering is a popular method to group similar data (e.g., via positional groups). Less advanced statistical modelling techniques may assume that each observation is independent, whereas other techniques, for example, Random-Effects Regression Models (RRM) do not assume this (Hedeker *et al.*, 1994). The use of techniques such as RRM, can be advantageous because outcomes at the individual level are modelled at both the individual- and cluster-level, whilst also estimating and accounting for the amount of intra-class correlation (i.e., variance) in the data (Hedeker *et al.*, 1994).

Beyond assessing one predictor variable at a time, there may have been a need to explore the interaction effects between workload variables, and between the types of external load (i.e., training/match volume, GPS/IMU loads, and contact loads). For instance, without fully understanding the interactions between workload variables (i.e., how acceleration loads may have been linked to HSR, or how PlayerLoad^{TM} may have been influenced by distance/contact data), it is hard to fully appreciate how these loads have actually contributed to an increased/decreased injury risk. Furthermore, by separating workload-injury relationships by the external loading type, this would have influenced how these loads are shown to influence injury risk (i.e., volume/GPS/contact alone rather than together). The encompassing impact of load on injury would have been an important area for further research. For instance, Rugby Union players are influenced by the duration, frequency and intensity of training/match play in every exercising scenario. Understanding how the volume, locomotive load and contact load interact for each player and the influence these interactions have on injury risk would potentially have had greater practical applications for coaches and practitioners (e.g., a player who spends a lower proportion of time training, but has a higher acceleration and contact load may have been at a higher injury risk than a player who had a greater volume but less acceleration and/or contact work per session).

6.5 PRACTICAL APPLICATIONS

6.5.1 Training Volume and Match Exposure

Chapter 3 investigated the association between mean weekly training volume and injury risk in elite Scottish Rugby Union players. The study highlighted that players who complete greater mean weekly training volumes (~ 7 hours per week) are the healthiest and most robust. It follows a similar methodological approach to that of Brooks *et al.* (2008), who reported that elite players should stay within 6.1 - 9.1 hours per week to reduce injury risk. A key difference between chapter 3 and Brooks *et al.* (2008), was that Brooks and colleagues, investigated acute weekly fluctuations in training volume, rather than mean weekly volume over a season. Due to the different approaches, Brooks showcases a higher severity risk at the upper end of their weekly volume spectrum (> 9.1 hours per week), whereas chapter 3 presents a lower risk. However, chapter 3 investigated absolute fluctuations in weekly training volume via cumulative training volume calculations. In turn, chapter 3 reported that an absolute weekly volume > 9.61 hours was significantly associated with a higher injury risk compared to the reference group, and is in line with the data reported by Brooks *et al.* (2008). The practical applications of these finding suggest that coaches and practitioners should aim to keep training volume around 7 hours per week and avoid high weekly training volumes above 9 hours. Although balancing the appropriate training volumes to maximise performance and minimise risk is a challenging task, these findings together provide a guideline for coaches to follow.

Chapter 3 highlights an increased injury risk for players involved in less than 15 matches per season. This may, however, be associated with injury reducing the number of games in which a player is available for selection (thereby reducing the number of games in which a player is involved in per season). Similarly, a higher match exposure (> 25 matches per season), which considerably reduced injury incidence and burden rates, may simply highlight that healthier, more robust players were injured less. For FGEs, it was reported that mean injuries per player is increased (i.e., the risk of sustaining an injury is increased over a 30-day period, see Supplementary Data), however, the incidence of match injury is actually reduced. Therefore, an important point of consideration is that greater match exposure may actually improve player robustness. Williams *et al.* (2017b), reported a higher injury risk for players with extremely high match involvements (> 35) over a season, and therefore, highlighted practical applications with regards to fixture scheduling and policies relating to player match exposure limits. Within this thesis, the research suggests that decisions should be made to not withhold players from match play involvements over extended periods where appropriate, as this may have a negative effect on injury risk if match robustness is lost. Players involved in at least 20 matches per season may have a substantially reduced risk compared to lower match exposures.

6.5.2 Workload Calculations for Training Volume and Pitch-based Workload

A key determinant of training volume and locomotive load in this study was the derived measures calculated from the volume and workload data. These included: 1-, 2- 3- and 4-weekly cumulative loads; absolute weekly changes in load; and various measures of acute: chronic workloads. For both volume and locomotive workload, high player loads were associated with a higher injury risk than lower loads over 1-weekly periods. The findings from these chapters (Chapter 3 and 4B) may highlight that from both a volume and intensity point of view, very high weekly loads should be avoided to reduce injury risk in professional Rugby Union players. It may be that very high volumes provide insufficient recovery periods for players, whereas very high intensity measures may induce unnecessarily high levels of fatigue, thereby increasing injury risk, particularly for match play scenarios. These findings may suggest that coaches and practitioners should consider minimising excessive player loads of weekly periods, both in terms of volume and locomotive pitch-based workload, however this requires further research based on the lack of data (particularly in Chapter 4B). Interestingly, weekly changes in volume reported no association with injury risk, whereas total distance over the same two seasons reported a trend in a significantly higher injury risk ($p < 0.05$) in this thesis. This likely reflects the lack of information provided from volume data alone. Players may be subjected to very different volumes from week-to-week, but unless there is some form of intensity measure to highlight the actual work performed within these weeks, it is difficult to comprehend how this may influence injury.

An important consideration for the volume and intensity measures used in this study was that daily ACWR data reported a linear relationship between training volume and injury risk as the ACWR increased above 1. This has previously been highlighted by Cummins *et al*. (2019), in professional Rugby League, and suggests that increasing volume above a player's current capacity will significantly increase injury risk. Therefore, gradual and systematic increases in volume should be considered within a periodised training programme when increases in volume are necessary to optimise player performance. This was not seen for pitch-based intensity measures via uncoupled ACWRs. It may be that training intensity can be altered more effectively and appropriately due to still being able to maintain appropriate recovery periods prior to match play. This is important for team coaches to consider, particularly in the in-season phase when matches are played at the end of the week. Indeed, such findings reinforce current practices already undertaken in elite Rugby Union, where higher pre-season volumes are completed compared to the in-season phase.

Chapter 4B highlights a key finding that is applicable to both research and practice in Rugby Union. That is, there are clear positional differences in Rugby Union in relation to the workloads performed (Supplementary Data). Investigating injury risk at the positional level allows coaches and practitioners to further understand the specific demands associated with that playing position, and how these demands ultimately influence injury. Unfortunately, although the differences in positional demands are shown, the injury data that coincides with this must be taken with caution. Nevertheless, these findings suggest that coaches and practitioners should consider the demands players are subjected to during training, and how recovery from these demands may help player performance and welfare when it comes to competing in Rugby Union matches. There is a need for further research to investigate the specific workloads/risks of injury at the positional level in elite Rugby Union.

6.5.3 The Contact Demands and Injury Risk of Rugby Union Match Play

The workload measurements adopted by Rugby Union clubs to monitor the loads of players over daily, weekly, monthly and seasonal periods can differ largely from club to club, and the expense of these measures also vary considerably. For instance, GPS systems with IMUs can cost in excess of hundreds of thousands of pounds per team, and there are multiple measures associated with these devices that are considered inaccurate on their own without further cross-examination. Therefore, an argument for more cost-effective methods for monitoring load and injury risk is an appropriate one given the lack of definitive answers that have presented in many load monitoring studies. Video coding analysis may be a more cost-effective and accurate method of assessing load in contact team sports. From the findings presented in chapter 5, it is clear that Forwards engage in more contact work than Backs. There is also an array of positional differences presented that can be used to adjust training practices and specialise specific areas of play for match readiness. An important factor presented in this study is that it appears not to be number of events engaged in, but the nature of the contact event that is more associated with contact injury. Although there is some scope to highlight that fatigue may increase injury risk in the 2nd half of match play, coaches and practitioners should ensure that tackling technique is a key area of practice.

A final practical application of chapter 5 is potential training modifications to certain player positions in light of their match loads and injury risk. For example, Scrum Half players are subjected to low contact loads and had one of the lowest distances covered out of any positional group. This data suggests that these players are exposed to low overall match loads from both a contact and running related perspective. Yet, these players did not report the lowest injury risk even though they are exposed to comparatively low loads in relation to other positional groups. This may tie into chapter 3 in such a way that these players may not lack match involvements, but they may lack match robustness through poor overall conditioning and a reduced contact and locomotive exposure. In this case, actually preparing these players beyond their relative match loads may be more optimal for minimising the risk of injury to Scrum Halves when they do engage in high impact events.

An important point of consideration with regards to video coding however is that it is a time intensive method of monitoring workload, and if this is applied to all pitch-based training sessions involving contact, and all matches, then the “burden” of this may be too great to warrant the use of more financially expensive methods. Therefore, given the financial and timely cost of different load-monitoring methods, it is important to consider the utility of current load monitoring practices.

6.5.4 A Consideration of Current Load Monitoring Practices

The workload data and injury data presented in this thesis varies considerably from study to study, depending on the loads investigated and the monitoring approaches adopted. There is currently a lack of agreement with regards to which approaches are best for monitoring loads and which are best for informing injury risk in Rugby Union. It is well-established from every avenue of load monitoring studies that the data presented may be associated with injury (Hulin & Gabbett, 2019), but none of it can accurately predict injury risk. It is important to understand that this is not due to entirely flawed load monitoring approaches or a lack of understanding as to how these loads can impact injury. Indeed, it would be ambitious to expect load monitoring studies to produce findings capable of predicting injury. Rather, it is the reality of the sport. In Rugby Union, even the most conditioned player can sustain a time loss injury if the nature of the contact event exceeds current tolerance. So it begs the question… from the time it takes to collect the data, to the financial cost it puts on the team, not to mention the current lack of consensus of which approaches are best for the given sport, is it worth it? (West, 2019). Load monitoring has increased rapidly in the last decade and is now common practice for improved performance player welfare, but the injury rates in Rugby Union are unchanged (Kemp *et al*., 2019, 2021). Kemp *et al*. (2021), reported that the 2019-20 season had a match injury incidence of 88 injuries per 1000 hours, which was very similar to that reported over the 2002 – 2019 period (87 injuries per 1000 hours). Furthermore, the 2019-20 season reported the highest average match injury severity of 38 days. The authors also reported a higher percentage of training injuries over the 2019-20 season (44%), compared to that of the 2002-19 period (32%). In addition, the training injury incidence rate was higher in the 2019-20 season (3 injuries per 1000 hours) compared to the 2002-19 period (2.5 injuries per 1000 hours). Noteworthy however, is that the Coronavirus pandemic (COVID19) resulted in matches being cancelled and training periodisation plans likely having to be drastically restructured to deal with the unique nature of the 2019-20 season. Furthermore, more of their time was spent training, which may have resulted in higher training injury incidence rates (Kemp *et al*., 2021). Nevertheless, these findings make it difficult to argue the need for load monitoring practices above that of other important aspects of injury and performance departments (i.e., strength and conditioning coaches, medical personnel etc.) (West, 2019).

There are however, considerations for the importance of load monitoring practices, and even more so, for research to provide fundamental practices that are capable of accurately and undoubtedly improving performance and player welfare. If all other components are in place, then load monitoring can help inform decisions with regards to player training protocols and injury risk reduction strategies (West, 2019). If these practices can prevent any injuries, particularly severe time loss injuries, then the expenses paid out to possess the most advanced load monitoring tools (e.g., GPS units with IMUs) are paid for simply through the outgoing wages to injured players (West, 2019). Therefore, at least in professional team sports, monitoring player loads is more than just helpful or interesting to look at, but should be an expectation of governing bodies to improve the current player welfare issues. There is however, need for clarity into which measures are actually worth monitoring and what the best approach is for monitoring loads to improve performance and reduce injury risk in elite Rugby Union.

In Chapter 5, section B of this thesis, there is evidence to highlight the varying results reported for injury incidence depending on the methods adopted to analyse injury data. The data presented showcases that certain measures may be more useful in determining how workload can influence injury risk, as well as reporting the different risks associated with different loads. Although this section cannot confirm exactly what measures are the most useful and provide most accurate results, it does highlight that the monitoring process, as well as the measures adopted and the analysis methods used needs to be truly considered. As it stands, there is not enough evidence for completely disregarding specific measures or to include others. It may be useful for future research to aim to towards creating a consensus statement on which measures are currently best practice.

6.6 FUTURE DIRECTIONS

A key aspect of this thesis was the novel investigation into external workloads, and the influence these loads have on injury risk in elite Scottish Rugby Union players. This was an important step in further understanding the workload-injury risk relationship in Rugby Union. However, given this specific focus, there were areas identified for future research. Firstly, each of the independent studies in this thesis addressed one specific type of load (i.e., volume/exposure, GPS/IMU workload, and contact events). These measures were then combined and compared in section B of chapter 5. Nevertheless, given the multifactorial circumstances of injury in team sport, there are likely a myriad of other external and internal factors that resulted in the injuries presented in this thesis. For example, volume may provide important information on training load, but it is difficult to fully understand the whole picture without adding an intensity measure to coincide with the data. Therefore, an important area of exploration would be to include multiple workloads when investigating injury risk to further understand the injury risk picture (i.e., to investigate multiple workload factors such as volume, GPS/IMU and contact data together to understand the load-injury relationship fully). Secondly, with no inclusion of additional internal/psychological loads on injury risk included in this thesis, our understanding of how certain external loads may have been linked to a higher injury risk via players' own unique perceptions/response of the given load is limited. Professional players have to deal with multiple stressors beyond those that are linked to training and match play. For instance, professional players' are likely to experience psychological stress in relation to pressures to consistently perform to the highest level (Mellalieu *et al*., 2021). In turn, this psychological pressure may be further exacerbated through illness or injury. Furthermore, there are also pressures associated with travel loads, sleep quality, family burdens, media engagement, etc. Therefore, an important avenue for future research to explore is the inclusion of both internal and external loads when investigating injury risk.

Beyond investigating the influence of various external and internal measures, it is important that the clubs involved in the study have set criteria beyond that of which they may want to monitor, at least from a research point of view. It is difficult to compare the data between teams unless there is some form of consistency with regards to the methods employed to collect training and match data, as well as internal loads (i.e., motivation, sleep quality, travel exhaustion etc.). A limitation of being able to include multifactorial approaches in this thesis was largely linked to team commitment, player adherence and overall agreement on the best methods to monitor and track injury risk. Indeed, differences in the monitoring approaches adopted between teams make the feasibility of large-scale studies including multiple teams over multiple seasons a substantial challenge. More collaboration in the methods adopted between clubs under the same Union would significantly improve the data collection process and accuracy of the data collected. In turn, this would translate into more practically applicable, evidence-based results that would better inform training strategies, such as periodisation structure and adaptation, as well as upper and lower limits for each player, thereby helping to improve both performance optimisation and overall player welfare.

A number of load monitoring studies in Rugby Union and other team sports have combined players for data and statistical analysis. Indeed, this improves statistical power via larger sample sizes, which in certain circumstances is needed to provide valid results. However, given the complete lack of reduction in injury rates (Kemp *et al*., 2019, 2021), it may be time to consider more detailed analysis of the positional requirements and demands associated with each player, and how these specific loads translate into a higher or lower injury risk. Importantly, this would require large-scale studies incorporating multiple teams or multiple seasons, and as aforementioned, the feasibility of collecting vast amounts of accurate data largely lies in the collaboration and consistency of the data collected from the clubs involved. If possible, this would drastically increase our understanding of the workload-injury relationship in Rugby Union, and, if this included multivariate analysis of internal and external loads, then the monitoring tools considered 'best practice', may be more easily identified for future research and practice. Indeed, the findings presented in this study for Chapter 4B and Chapter 5 highlight substantial positional differences in external workloads, and this would likely also be seen for internal and psychological stresses also, and how these loads together influence injury risk.

Similar discussions can be had with the monitoring tools and variables used to collect workload data. Simple and effective practices that are comparatively cheap to the advanced technological tools often used in elite team sports settings today (e.g., GPS) were used in chapter 5 of this thesis (video coding). Furthermore, the workload measures used in this thesis were compared in Chapter 5, section B, which has provided some evidence of the importance of considering the workload measures used and the analysis methods adopted to investigate workload-injury relationships. This study presented novel findings for professional Rugby Union teams to consider when evaluating the contact demands of positional groups, and provides a foundation on which future research can build upon without spending considerable capital on the latest gadgets. There is a need to comprehensively evaluate each individual type of load within Rugby Union before we can fully understand the impact of such load on injury. Importantly, this can be achieved whilst still accounting for other types of workload as well (and should be considered as only part of the process). For instance, it has been reported that video analysis methods trump IMUs when investigating contact data due to the inaccuracy of these devices to identify contact events compared to other high acceleration/deceleration movements (Reardon *et al.*, 2017a). Therefore, although a time consuming process, if researchers and teams alike can put time aside to video code matches, then this may be an effective, cheaper and potentially more accurate alternative. Alternatively, video coding could be used in conjunction with IMU data to understand the actual contact loads of Rugby Union for every player, and the G-forces associated with these events.

A final point of consideration for both research and practice, is that injury is always assessed from a point of view that looks to minimise the risk for 'at risk' players, yet currently there is no evidence to suggest this has had any influence on Rugby Union injury rates. It is important to understand that methods that may reduce risk in one scenario, may increase risk in another. For instance, lower loads may reduce injury risk simply through a decrease in volume and/or intensity preventing that player from overwhelming the structural integrity of the musculoskeletal soft tissue. However, reductions in training volume/workload are also likely to result in deteriorations to physical attributes and, possibly skill execution. This in turn, may add to injury risk when the player is exposed to increased loads or is placed within a match situation. Therefore, such methods may seem plausible from a research perspective, but may be futile from a practical point of view. One aspect that was presented for the volume data in chapter 3, was that healthy and robust players who averaged ~ 7 hours per week of training over a season, had a considerable reduction in both injury incidence and burden. The differences between these players and those who sustained one or multiple time-loss injuries is not known. However, it may be worthwhile identifying these robust players that perform week in and week out, and with enough workload variables (e.g., volume, running data, contact data, psychological measures…), an investigation into specific differences between the most 'at risk' compared to the most 'robust', may be a better method for investigating loads vs. injury risk for research. This may be a more fruitful process of investigating workloads and injury, rather than simply addressing what aspects of single workload measures resulted in a higher injury risk for certain players.

6.7 CONCLUSION

The aim of this thesis was to present novel findings in relation to the training and match loads associated with professional Rugby Union, and how these loads influence injury risk. To achieve this aim, four research questions were developed, and through the collaboration with the SRU, these were answered via the workload data and materials provided from the professional clubs involved. Training volume was shown to follow similar patterns to that of professional Rugby Union research previously presented in the English Premiership teams over multiple seasons (West *et al*., 2019). Chapter 3 further identified mean weekly volumes that healthy and robust players are exposed to on a weekly basis to perform week in and week out (i.e., 7 hours per week). This thesis also reinforced previous observations from a 7 season prospective study conducted by Williams *et al.* (2017b), reporting that players who are exposed to more matches over the course of a season (≥ 25 in this thesis) have a lower injury risk than players with lower match involvements, particularly less than 15. Currently, there is a lack of research in Rugby Union identifying how GPS and IMU workload data are related to injury in this sport. Therefore this thesis provides a foundation on which future research can build upon. Within Chapter 4B and 5, (positional differences for 4B provided in Supplementary Tables) positional analysis highlighted the relative demands of the sport for Scottish Rugby Union players. The data presented in these chapters varied considerably, and provides scope for future research to include both metrics when investigating the varying external loads imposed on professional players.

The data presented in this thesis highlights the importance of utilising load monitoring to inform injury risk at the professional level of Rugby Union. Through measures of external load across multiple teams, the evidence presented gives coaches and practitioners avenues in which workload can be investigated to further improve training protocols for match preparation and, ultimately, performance and player wellbeing.

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APPENDICES

APPENDIX A:

Player Information Sheet for Chapter 4A

Player Information Sheet

Title: The Interunit Reliability of Two 10-Hz Global Positioning System Devices to Report Total Distance during Rugby Union Pitch-Based Training

Principal Investigator/researcher: Mr Cameron Paul

Academic Supervisors: Dr Debbie Palmer and Dr Tom Campbell

External Supervisor: Mr Stuart Yule

Independent Advisor: Dr Craig Stevens

You are invited to take part in the first part of a research study investigating the association between training and match work rates on time-loss injury in elite Scottish Rugby Union. This study is fully supported by the Scottish Rugby Union, and will strictly adhere to the SRU data collection procedures. Before deciding whether to take part or not, the following information will outline why the study is being undertaken and how you will be involved. If you have any questions regarding the study, please direct them to a member of staff at your club, such as your medical officer or strength and condition coach, or you can contact us for any further questions.

Study Aim

The aim of this study is to determine the relationship between Rugby Union training and match play work rates and the incidence/severity of injury in elite Scottish Rugby Union. This study will investigate the influence of position specific training and match work rates as risk factors for injury, and will reveal how the structure of a training programme can influence the risk of injury in a given season. In addition, this study will compare the accuracy and validity of micro-technology devices (e.g. Catapult Optimeye S5 devices; GPSports SPI High Performance Units; Statsports Apex Pods; Global Rugby Network Video Analysis Software) used by the Scottish Rugby Union to measure training and match play work rates to ensure the work rates reported are reliable and valid.

What does the study involve?

Prior to assessing the influence of training and match work rates on injury risk, a comparison of the micro-technology devices (Catapult Optimeye S5 devices; Catapult Sports, Canberra, Australia; GPSports SPI High Performance Units, GPSports, Sydney, Australia; Statsports Apex Pod, Statsports, Newry, Northern Ireland; Global Rugby Network Video Analysis Software, Global Rugby Network, Glasgow, Scotland) used by the Scottish Rugby Union's professional teams is needed. The reason for this is due to Scottish Rugby Union professional teams using different devices to monitor training and match movement patterns and contact events. Currently it is not known if these devices report different results for the same session. Therefore, while completing their normal pitch-based training sessions, academy and club players are asked to wear a dual pouch vest harnessing the two devices used by the professional teams at the same time. Thereafter the data reported from the two devices can be analysed for potential differences.

Who is being asked to participate in the study?

All first team players playing for the Scotland Under 18 and 20 Academy Squads, Edinburgh Rugby Academy Squad, Glasgow Warriors Academy Squad, and teams within the Scottish BT National 1 Leagues (Scottish BT National 1 League, Scottish BT National Reserve League Division 1 and BT East Reserve League Division 1) who are 16+ will be asked to take part in the study.

Are there any risks from taking part?

There are no risks involved in this study that go beyond your daily training activities.

What will happen to the data obtained from the research study?

Data collected in this study will be analysed by the researchers mentioned above at Edinburgh Napier University to investigate potential differences between the two devices.

Contact Details

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APPENDIX B:

Player Consent Form for Chapter 4A

Player Consent Form

I confirm that I have read and understood the information outlined in the player information sheet for this study. I have had the opportunity to ask questions and I am satisfied that my questions have been answered prior to participating in this study.

I agree to participate in this study and give permission for the fitness staff within my club to supply the training data to the researchers at Edinburgh Napier University. I understand that all information provided by the fitness staff will be used for research purposes, and that all data shall be presented as group averages, so that individual values are not reported in any published material.

I understand that all of my training work rate data will be treated with the strictest confidence, will always remain anonymous, and will be protected on a secure online platform.

I understand that I can withdraw from this study at any point and will not be required to provide a reason for withdrawing. This can be achieved by asking the primary researcher (Cameron Paul) or asking any member of the coaching staff prior to, during or on completion of the study. On the decision to withdraw following data collection, the data will not be used during the analysis stage, and will be deleted.

Print Name___________________________

Signed____________________________

Date______________________________

APPENDIX C:

Monitoring Training & Match Exposure in Elite Scottish Rugby Union

Mr Cameron Paul[1], Dr Tom Campbell[1], Mr Stuart Yule[2], Dr Debbie Palmer[1]

[1]School of Applied Sciences, Edinburgh Napier University, Edinburgh, UK.

[2]Scottish Rugby Union, Murrayfield, Edinburgh, UK

BACKGROUND

Training and match exposure has been shown to influence injury risk in elite Rugby Union players

OBJECTIVE

To show how different load-measures can be used to quantify player training and match exposure over a professional Rugby Union season.

DESIGN

A prospective, observational cohort study design was adopted to collect exposure data for all gym and pitch-based training sessions & competitive matches.

SETTING

Data were collected from Scottish Rugby Union's professional (Men's 15-a-side) teams (Men's International Squad; Glasgow Warriors and Edinburgh Rugby) for training and match play purposes.

PATIENTS (OR PARTICIPANTS)

All first team players (n = 148) were eligible to be included in this study from the three professional teams included.

INTERVENTIONS (OR ASSESSMENT OF RISK FACTORS)

Gym & pitch-based training and match play data were collected over the 2017/18 season via weekly team logs & Global Positioning System (GPS) devices.

MAIN OUTCOME MEASUREMENTS

Weekly exposure was calculated by summing each 7-day period over the season. Acute: chronic workload ratio (ACWR) measures (rolling and exponentially weighted moving average; EWMA) were then calculated, as well as week-to-week absolute changes in exposure, and 2-, 3- and 4-week cumulative exposures.

RESULTS

Throughout the season, players spent a total of 28737.9 hours in training, and 1649.3 hours in match play. On average, players were exposed to 6.51 (±3.15) hours of training and match play per week. Squads averaged 542.6 (±212.0) hours of training and match play per week. On average, weekly ACWRs were 0.75 (±0.17) (EWMA), and 0.96 (±0.27) (rolling); week-to-week change in exposure was 129.5 hours (± 119.3); Cumulative 2-, 3- and 4-week exposures were 1083.3 (±416.5), 1623.1 (±600.3) and 2161.1 (±778.6) hours, respectively

CONCLUSIONS

Depending on the measures adopted, team coaches and practitioners will see a different impression of how the exposure data collected over a season may influence injury risk.

APPENDIX D:

The Influence of Training Volume on Training and Match Injury Risk in Elite Scottish Rugby Union Players

Mr Cameron Paul[1], Dr Tom Campbell[1], Mr Stuart Yule[2], Mr Jack Walsh[2], Dr Russell Martindale[1], Dr Debbie Palmer[1]

[1]School of Applied Sciences, Edinburgh Napier University, Edinburgh, UK.

[2]Scottish Rugby Union, Murrayfield, Edinburgh, UK.

BACKGROUND

Training volume has been shown to influence injury risk in elite Rugby Union players.

OBJECTIVE

To investigate the influence of training volume on injury risk in elite Scottish Rugby Union players.

DESIGN

A prospective, observational cohort study design was adopted to collect training volume (hours) and injury data (training and match time-loss injuries combined).

SETTING

Data were collected from Scottish Rugby Union's professional (Men's 15-a-side) teams (Men's International Squad; Glasgow Warriors and Edinburgh Rugby).

PATIENTS (OR PARTICIPANTS)

Data were collected from 163 professional Rugby Union players over the 2017/18 and 2018/19 seasons.

INTERVENTIONS (OR ASSESSMENT OF RISK FACTORS)

Gym & pitch-based training data were collected via team logs & Global Positioning System devices. Injury data were collected from the medical personnel associated with each team.

MAIN OUTCOME MEASUREMENTS

Derived workload measures were calculated. These included: the exponentially-weighted moving average acute: chronic workload ratio (ACWR); week-to-week change in volume, and 1- 2-, 3- and 4-week cumulative volumes. Workload measures were modelled against subsequent week injury using binary logistic regression analysis. Odds ratios (OR) were reported against a reference (‘Very-low’ workload) group.

RESULTS

Players spent a total of 58,044 hours training, and sustained 734 time-loss injuries. Compared to the reference category (<0.50), an 'Intermediate-low' ACWR (0.75-1.00) had the lowest injury risk (OR=0.46). Contrary, an 'Intermediate-high' (1.00-1.25), 'High' (1.25-1.50) and 'Very-high' (>1.50) ACWR significantly increased injury risk (OR=4.85, 13.36 and 15.70, $p<0.001$, respectively). Injury risk was significantly increased for 'Intermediate-low' training volumes over 1-3 week cumulative periods, and ‘Intermediate-high' volumes over 2-4 week cumulative periods. 'Very-high' volumes increased injury risk over 1-3 week cumulative periods. 'High' training volumes over 1-4 weeks and weekly change in volume were not associated with injury ($p>0.05$).

CONCLUSIONS

Increases in acute training volume beyond a player’s current chronic status may increase injury risk. Minimising spikes in volume, whilst gradually acquiring high training volumes may be more protective against injury than intermediate and very high volumes.

APPENDIX E:

Understanding the Match and Training Volume-Injury Relationship in Elite Scottish Rugby Union (Chapter 3) – Supplementary Data

Total Training Volume

When split into professional club vs. international environments, players spent a total of 53,277.5 hours (On-pitch training: 37,775.2 player-hours; Gym-based training: 15,502.3 player-hours) training at their professional club, compared to 4,766.8 player-hours (On-pitch training: 3,888.3 player-hours; Gym-based training: 878.5 player-hours) at their International squad. For Forwards, this equated to 29,556.1 hours (On-pitch training: 21,085.9 player-hours; Gym-based training: 8,470.2 player-hours) at their professional club, compared to 2,796.7 hours (On-pitch training: 2,274.9 player-hours; Gym-based training: 521.8 player-hours) at the International environment. For Backs, players spent a total of 23,721.5 hours (On-pitch training: 16,689.4 player-hours; Gym-based training: 7,032.1 player-hours), at their professional club, compared to 1,970.1 hours (On-pitch training: 1,613.4 player-hours; Gym-based training: 356.7 player-hours), at the International environment.

Mean Weekly Squad Training Volumes

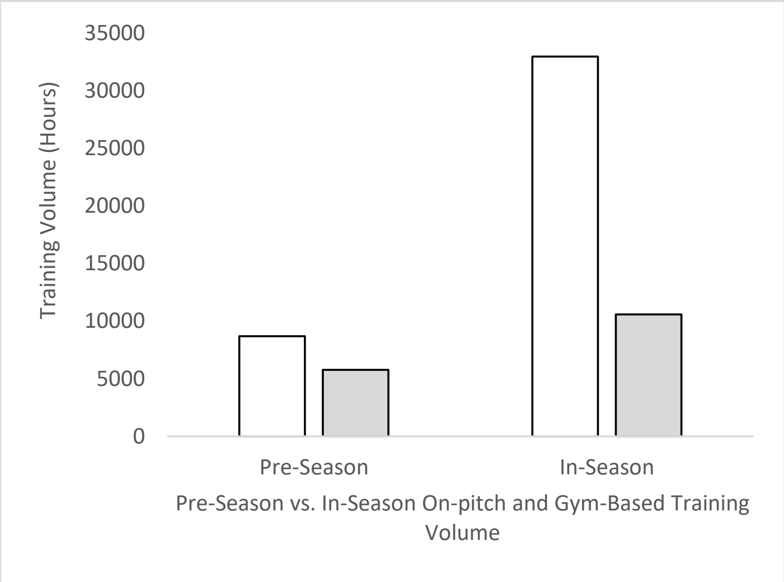
Professional squads averaged 538.2 (± 194.4) hours of training per week (On-pitch training: 381.6 [± 137.9] player-hours; Gym-based training: 156.6 [± 92.0] player-hours). For Forwards and Backs, this equated to 298.5 (± 110.5) hours (On-pitch training: 213.0 [± 78.4] player-hours; Gym-based training: 85.6 [± 50.0] player-hours), and 239.6 (± 87.0) hours (On-pitch training: 168.6 [± 62.8] player-hours; Gym-based training: 71.0 [± 42.8] player-hours), respectively. The International squad averaged 113.5 (± 53.4) hours of training per week (On-pitch training: 92.6 [± 40.8] player-hours; Gym-based training: 20.9 [± 15.4] player-hours). For Forwards and Backs, this equated to 66.6 (± 31.2) (On-pitch training: 54.2 [± 23.4] player-hours; Gym-based training: 12.4 [± 9.6] player-hours), and 46.9 (± 27.4) (On-pitch training: 38.4 [± 21.8] player-hours; Gym-based training: 8.5 [± 6.8] player-hours), training hours per week, respectively.

Mean Weekly Player Training Volumes

When training at their professional club, players averaged 6.6 (± 3.3) hours of training per week (On-pitch training: 5.0 [± 2.5] player-hours; Gym-based training: 2.6 [± 1.7] player-hours). Forwards completed 6.6 (± 3.4) hours of training per week (On-pitch training: 5.1 [± 2.5] player-hours; Gym-based training: 2.6 [± 1.7] player-hours), and Backs completed 6.6 (± 3.2) hours of training per week (On-pitch training: 4.9 [± 2.5] player-hours; Gym-based training: 2.6 [± 1.7] player-hours). When called up for International duty, players averaged 5.3 (± 2.1) hours of training per week (On-pitch training: 5.0 [± 2.5] player-hours; Gym-based training: 2.6 [± 1.7] player-hours). Forwards completed 5.5 (± 2.1) hours of training per week (On-pitch training: 4.5 [± 1.6] player-hours; Gym-based training: 1.3 [± 0.6] player-hours), and Backs completed 5.1 (± 2.1) hours of training per week (On-pitch training: 4.2 [± 1.7] player-hours; Gym-based training: 1.2 [± 0.5] player-hours).

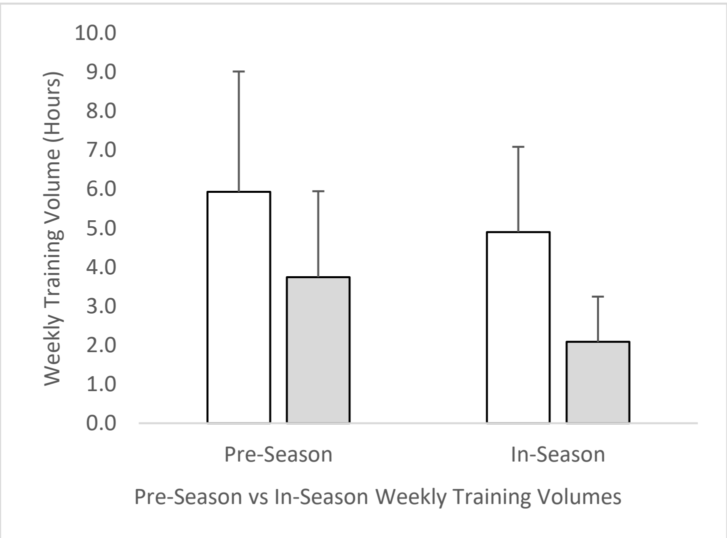
Training Activity Volume over the Pre-Season and In-Season

During the pre-season phase, players spent a total of 8,709 player-hours completing on-pitch training, compared to 5,787 hours completing gym-based training. During the in-season phase, players completed 32,955 hours of on-pitch based training, compared to 10,593 hours of gym-based training (see Supplementary Figure 1). Players averaged 5.9 (± 3.1) hours of on-pitch training per week, compared to 3.8 (± 2.2) hours of gym-based training per week over the pre-season. In the in-season, players averaged 4.9 (± 2.2) hours of on-pitch training per week, compared to 2.1 (± 1.2) hours of gym-based training per week (see Supplementary Figure 2). Forwards averaged 6.1 (± 3.1) hours of on-pitch training per week, compared to 5.8 (± 3.1) hours of on-pitch training for Backs over the pre-season. During the in-season phase, Forwards averaged 4.96 (± 2.14) hours of on-pitch training per week, and Backs averaged 4.82 (± 2.2) hours. For gym-based training, Forwards averaged 3.72 (± 2.3) hours of training per week, compared to backs who averaged 3.78 (± 2.1) hours per week. During the in-season phase, Forwards averaged 2.1 (± 1.10) hours of training per week, and Backs averaged 2.1 (± 1.2) (see Supplementary Figure 3).



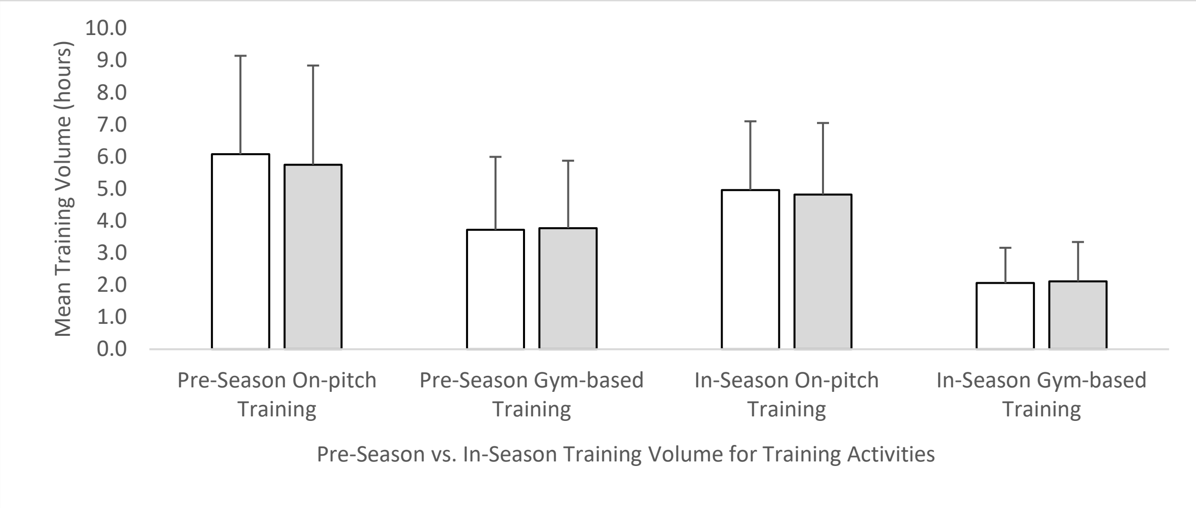
Supplementary Figure 1: Total time players engaged in on-pitch and gym-based training over the 2017/18 and 2018/19 pre-season and in-season.

NOTE: White bars, on-pitch training; grey bars, gym-based training.



Supplementary Figure 2: Mean weekly training volume per player for on-pitch vs. gym-based training over the pre-season and in-season phases.

NOTE: White bars, on-pitch training; grey bars, gym-based training.

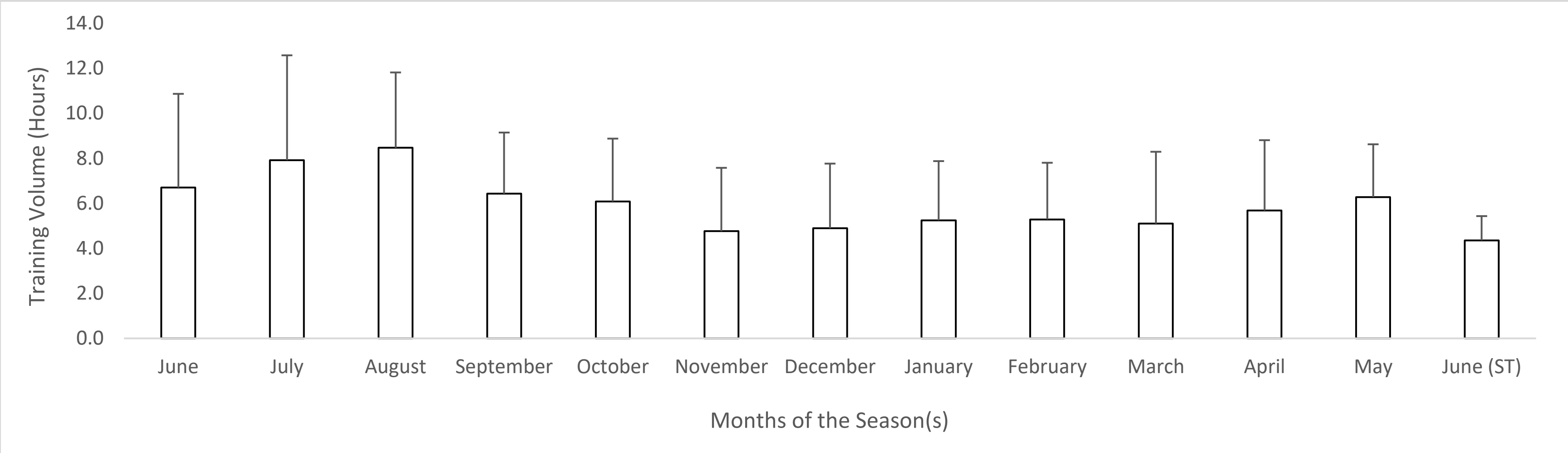


Supplementary Figure 3: Mean on-pitch and gym-based training volumes per player per week over the pre-season and in-season phases for Forwards and Backs.

NOTE: White bars, Forwards; grey bars, Backs.

Monthly Training Volume

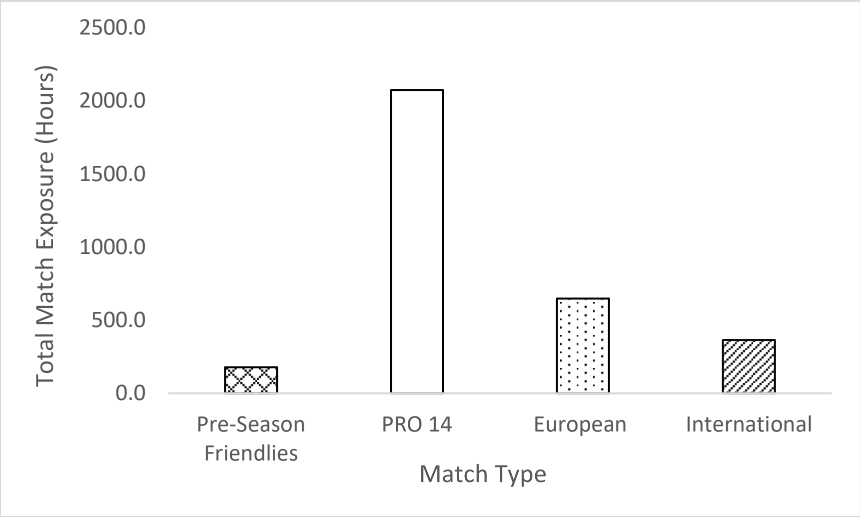
Throughout the study, monthly differences in training volume were evident. At the start of pre-season (June), players were training for 6.7 (± 4.2) player-hours per week. This gradually increased to 7.9 (± 4.7) player-hours per week in July, and further increased to 8.5 (± 3.4) player-hours in the final month of the pre-season (August). Training volume thereafter dropped in September to 6.4 (± 2.7) player-hours per week, and continued to decrease through to November (4.8 [± 2.8] player hours per week). Training volume thereafter gradually increased through to May (6.3 [± 2.3] player-hours per week) (see Supplementary Figure 4). During the season, the focus of training and time spent in different training categories changed. There was a priority in gym-based training at the start of the pre-season (i.e., June), as players averaged 4.2 (± 2.7) player-hours per week, compared to 3.4 (± 2.4) player-hours of on-pitch training. In July, on-pitch training was the main priority, as players were completing 5.2 (± 3.1) hours of on-pitch work, compared to 3.6 (± 2.3) hours of gym-based work. In August, this on-pitch training priority further increased, as players averaged 6.0 (± 2.6) player-hours of on-pitch training per week, compared to 3.0 (± 1.5) player-hours of gym-based work. Throughout the in-season phase, the priority of on-pitch work was maintained (gym-based = 2.0 [± 1.1]; on-pitch = 4.5 [± 2.3] player-training hours per week during the in-season phase) (see Figure 3.10).



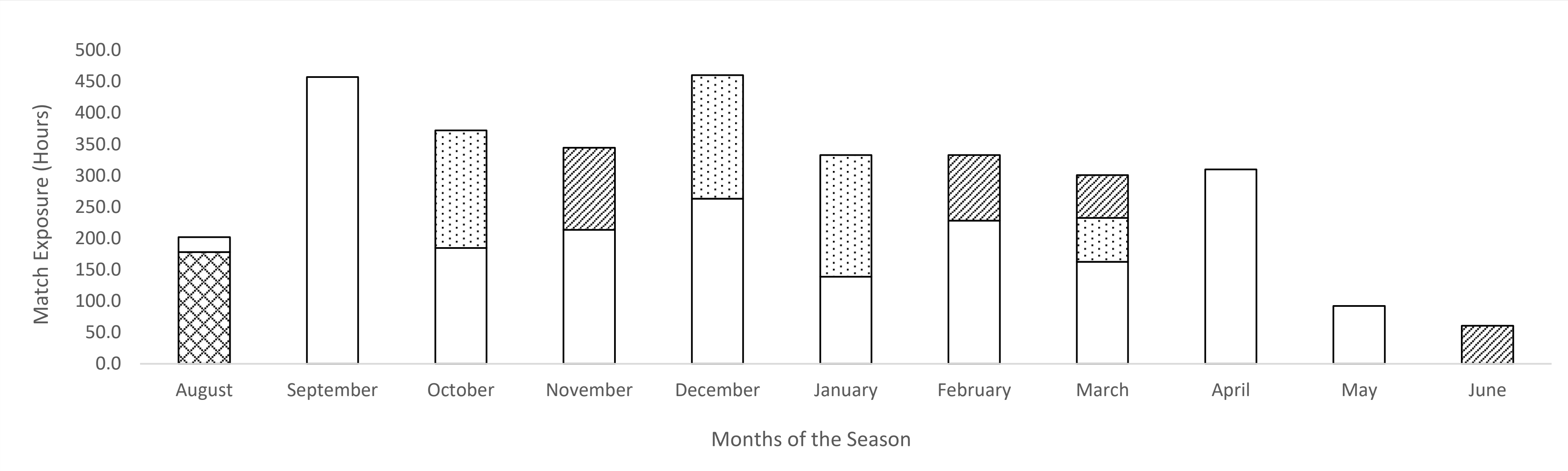
Supplementary Figure 4: Mean training volume per player per week for each month over the 2017/18 and 2018/19 seasons.

NOTE: June ST, June (summer tour)

Total Match Exposure and Total Monthly Match Exposure



Supplementary Figure 5: Total match exposure over the 2017/18 and 2018/19 seasons for pre-season friendlies, PRO 14, European and International matches.

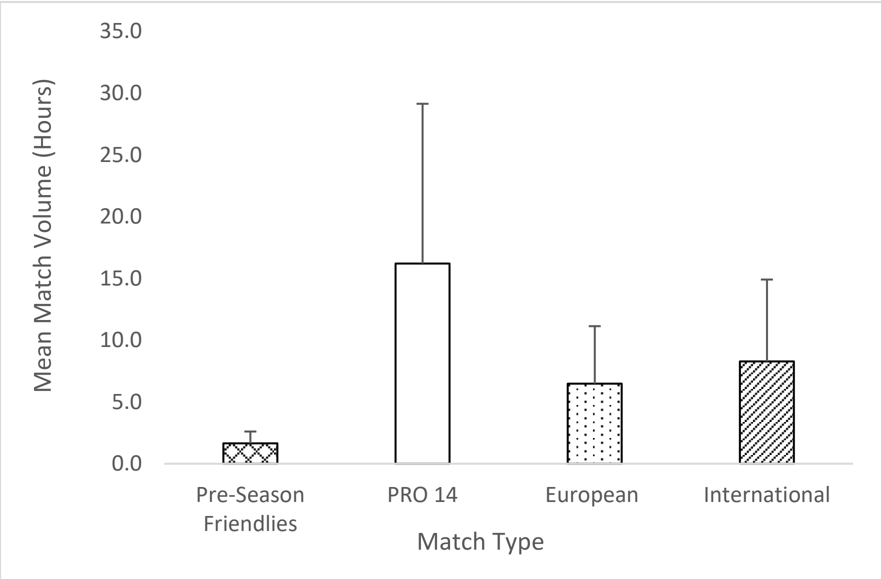


Supplementary Figure 6: Total match exposure over each month of the 2017/18 and 2018/19 seasons for pre-season friendlies, PRO 14, European and International matches.

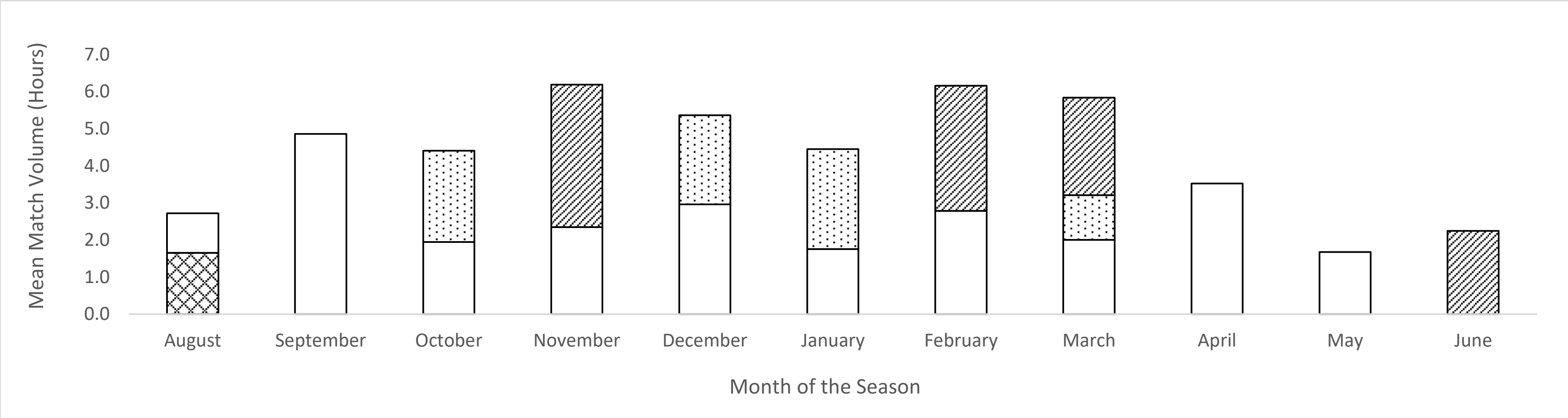
NOTE: International exposure in June represents the 2017/18 summer tour; diamond bar, Pre-season friendlies; white bar, PRO 14 matches; dotted bar, European matches; stripped bar, International matches.

Mean Match Volume

Players had the lowest mean match volume for pre-season friendly matches, averaging 1.7 (± 1.0) hours of total volume over the two seasons. Players spent the greatest proportion of their match volume competing in the PRO 14, with players engaging in 16.2 (± 12.2) hours over the two seasons. For European and International matches, players averaged 6.5 (± 4.7) and 8.3 (± 6.6) hours of match play over the study period, respectively (see Supplementary Figure 7). The mean match volume for each match type over each month is provided in Supplementary Figure 8.



Supplementary Figure 7: Mean match exposure for each match type over the 2017/18 and 2018/19 seasons.



Supplementary Figure 8: Mean match exposure over each month of the 2017/18 and 2018/19 seasons for pre-season friendlies, PRO 14, European and International matches.

NOTE: International exposure in June represents the 2017/18 summer tour; diamond bar, pre-season friendlies; white bar, PRO 14 matches; dotted bar, European matches; stripped bar, International matches.

Training and Match Injury Data

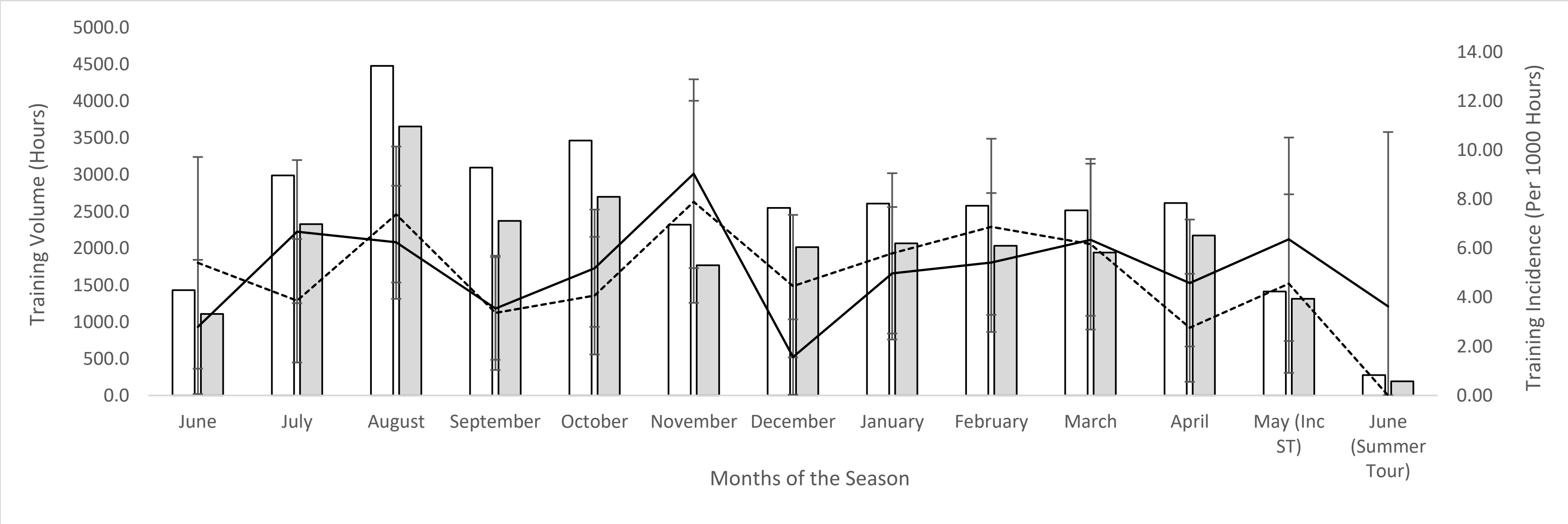
When split into pre-season and in-season phases, a total of 89 training injuries were sustained during the pre-season (Forwards = 50, Backs = 39), in which 69 occurred during pitch-based training (Forwards = 36, Backs = 33), and 11 were sustained during gym-based training (Forwards = 6, Backs = 5). A total of 216 injuries occurred during the in-season phase (Forwards = 121, Backs = 95), of which 189 occurred during on-pitch training (Forwards = 105, Backs = 84), and 13 occurred during gym-based training (Forwards = 9, Backs = 4). Of the 429 match injuries, 25 were sustained during the pre-season (Forwards = 11, Backs = 14), and 404 were sustained during the in-season (Forwards = 212, Backs = 192). Players sustained 25 injuries during pre-season friendly matches (Forwards = 11, Backs = 14), 275 injuries (Forwards = 136, Backs = 139) during PRO 14 matches, 79 injuries (Forwards = 47, Backs = 32) during European matches and 50 injuries (Forwards = 29, Backs = 21) during International matches.

Training Injury Incidence

When split into pre-season and in-season phases, training incidence rates were 6.1 (95% CIs: 4.9–7.4) injuries per 1000 pre-season player-training hours (Forwards = 6.2 [95% CIs: 4.5–7.9]; Backs = 6.1 [95% CIs: 4.2–7.9]), compared to 5.0 (95% CIs: 4.3–5.6) injuries per 1000 in-season player-training hours (Forwards = 5.0 [95% CIs: 4.1–5.9]; Backs = 4.9 [95% CIs: 3.9–5.9]). On-pitch training in both the pre-season (pre-season on-pitch = 7.9 [95% CIs: 6.1–9.8] injuries per 1000 player-hours [Forwards = 7.4, 95% CIs: 5.0–9.8; Backs = 8.6, 95% CIs: 5.7–11.5]) and in-season (in-season on-pitch = 5.7 [95% CIs: 4.9–6.6] injuries per 1000 hours [Forwards = 5.7, 95% CIs: 4.6–6.8; Backs = 5.8, 95% CIs: 4.6–7.0]) had a much higher incidence than gym-based training (pre-season gym-based training = 1.9 [95% CIs: 0.8–3.0] injuries per 1000 player-hours [Forwards= 1.9, 95% CIs: 0.4–3.4; Backs = 1.9, 95% CIs: 0.2–3.6]; in-season gym-based = 1.2 [95% CIs: 0.6–1.9] injuries per 1000 hours [Forwards = 1.5, 95% CIs: 0.5–2.6; Backs = 0.8, 95% CIs: 0.0–1.7]).

When split into months of the season, June had an incidence rate of 3.9 injuries per 1000 player-training hours (Forwards = 2.8 [95% CIs: 0.01–5.5]; Backs = 5.4 [95% CIs: 1.1–9.7]), and July had an incidence rate of 5.5 injuries per 1000 player-training hours (Forwards = 6.7 [95% CIs: 3.8–9.6]; Backs = 3.9 [95% CIs: 1.3–6.4]). August, which had the highest training volume for any given month, reported the second highest incidence rate across the study of 6.8 injuries per 1000 player-training hours (Forwards = 6.3 [95% CIs: 3.9–8.6]; Backs = 7.4 [95% CIs: 4.6–

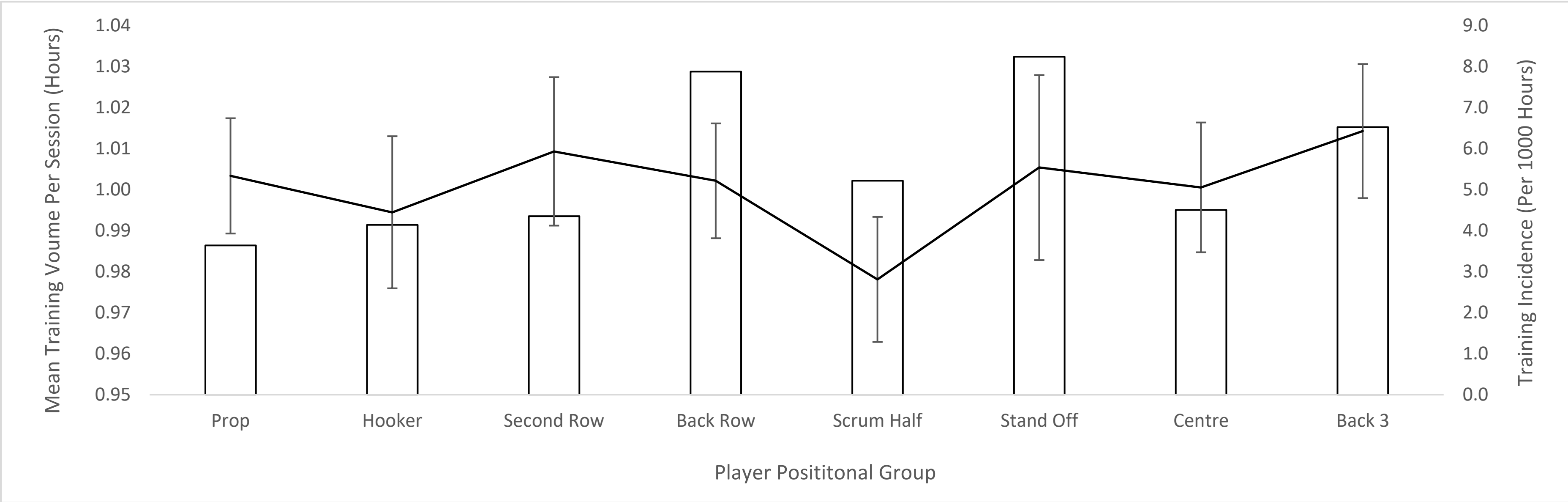
10.2]). The month of November, which had one of the lowest training volumes over the study, had the highest incidence rate of 8.6 injuries per 1000 player-training hours (Forwards = 9.1 [95% CIs: 5.2–12.9]; Backs = 7.9 [95% CIs: 3.8–12.0]) (See Supplementary Figure 9 for Forward and Back monthly training volumes and corresponding incidence rates).



Supplementary Figure 9: Training incidence rates for forwards and backs with total training volume across each month of the season.

NOTE: International exposure in June represents the 2017/18 summer tour; white bars, Forwards training volume; grey bars, Backs training volume; solid line, Forwards training incidence; dashed line, Backs training incidence.

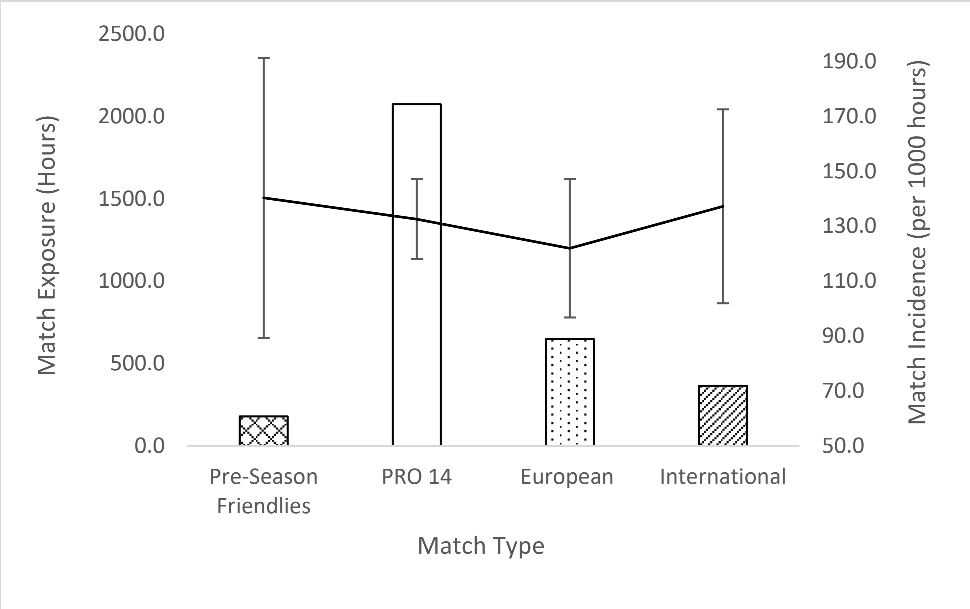
Mean training volume per session for each SRU positional grouping, and corresponding training incidence rates are shown in Supplementary Figure 10. Props had the lowest mean training volume per session, but the second highest incidence rate (5.3 [95% CIs: 3.9–6.7] injuries per 1000 player-training hours) out of the Forwards. Second Row players had similar mean training volumes to Hookers, but had much greater incidence rates (5.9 [95% CIs: 4.1–7.7] injuries per 1000 player-training hours and 4.4 [95% CIs: 2.6–6.3] injuries per 1000 player-training hours, respectively). Backrow players had the highest mean training volume per session for Forwards, with an incidence rate of 5.2 [95% CIs: 3.8–6.6] injuries per 1000 hours. Backs reported a more systematic pattern, in which decreased training volume per session resulted in lower injury rates. This was seen was for Scrum Halves and Centres (2.8 [95% CIs: 1.3–4.3] injuries per 1000 player-training hours; 5.1 [95% CIs: 3.5–6.6] injuries per 1000 player-training hours). Stand Offs and the Back 3 had higher mean training volumes per session, and this was reflected in their incidence rates (5.5 [95% CIs: 3.3–7.8] injuries per 1000 player-training hours; 6.4 [95% CIs: 4.8–8.1] injuries per 1000 player-training hours, respectively).



Supplementary Figure 10: Mean player training volumes per sessions for Scottish Rugby Unions positional groupings with positional training incidence rates.

NOTE: White bars, mean training volume; solid line, training incidence; error bars, 95% confidence intervals.

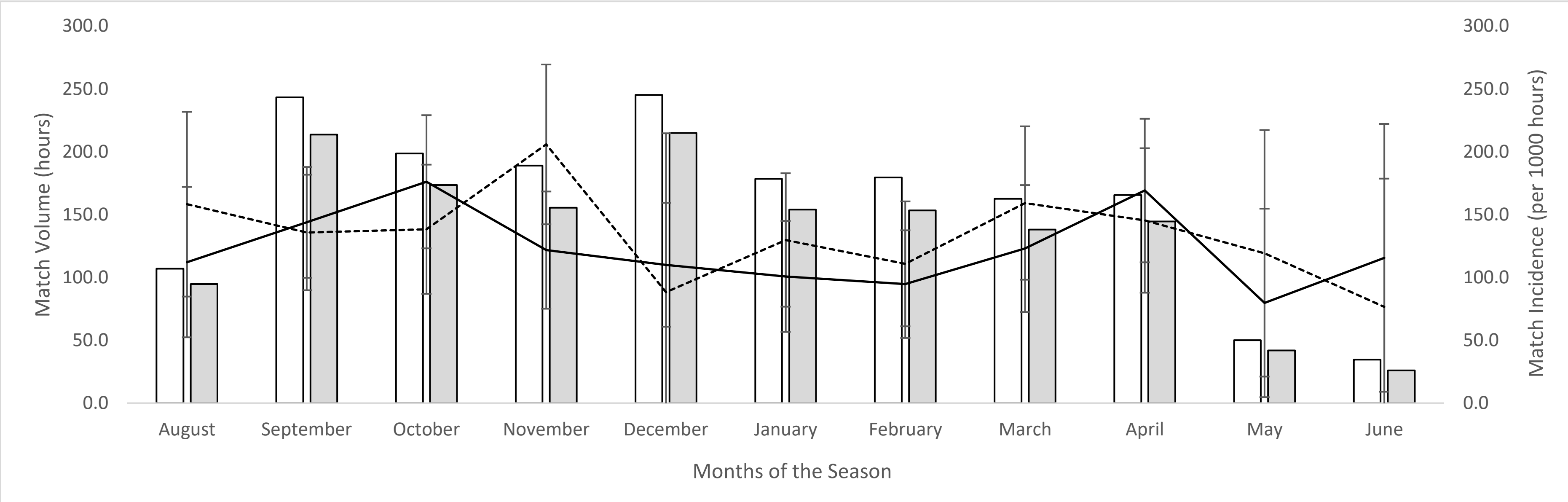
Match Injury Incidence



Supplementary Figure 11: Match incidence rates for the different match types players were competing in over the 2017/18 and 2018/19 seasons.

NOTE: Errors bars, 95% confidence intervals.

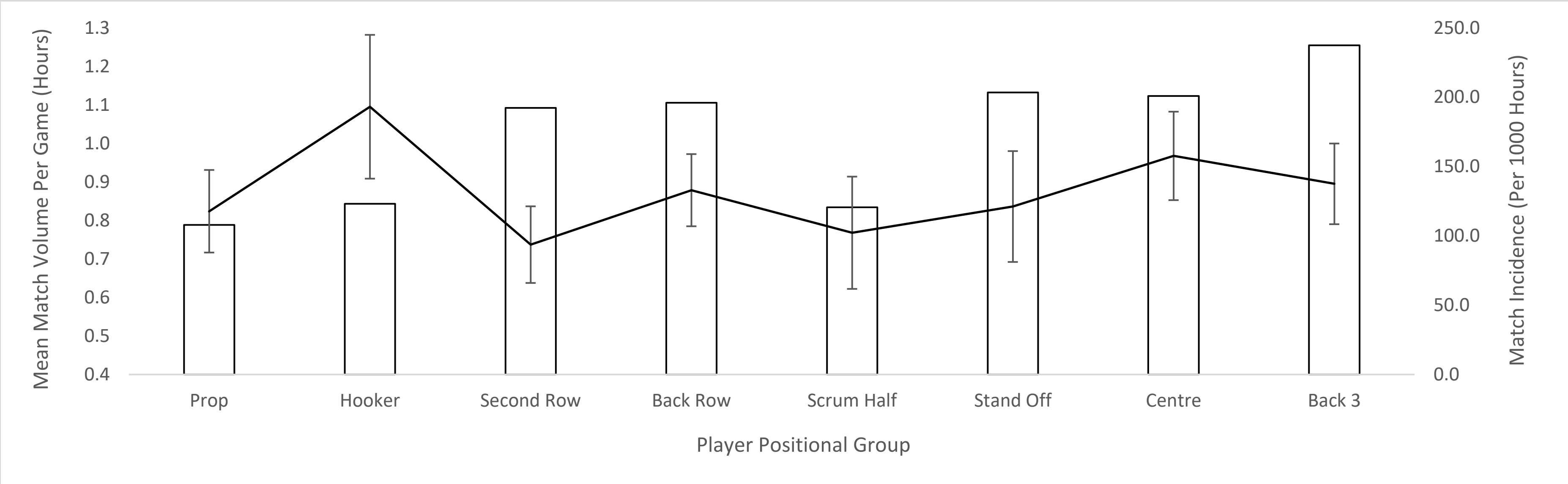
Match incidence rates gradually increased from pre-season matches in August (112.2 [95% CIs: 52.4 – 172.0] injuries per 1000 match hours) and peaked in October for Forwards (176.1 [95% CIs: 123.1 – 229.1] injuries per 1000 match hours). Forwards match incidence increased in March again (123 [95% CIs: 72.5 – 173.5] injuries per 1000 match hours), and was very high in April (169.2 [95% CIs: 112-226] injuries per 1000 hours). Match incidence increased rapidly for Backs in November (205.9 [95% CIs: 142.3–269.4] injuries per 1000 hours), after remaining low throughout the early months of August - October (see Supplementary Figure 12), and dropped substantially again in December (88.4 [95% CIs: 50.6 – 126.3] injuries per 1000 hours). Match incidence thereafter rose in January (130 [95% CIs: 76.7 – 182.9), and increased largely again in March for Backs (159.2 [95% CIs: 98.2 – 220.2] injuries per 1000 hours)



Supplementary Figure 12: Match incidence rates for Forwards and Backs with total match volume across each month of the season.

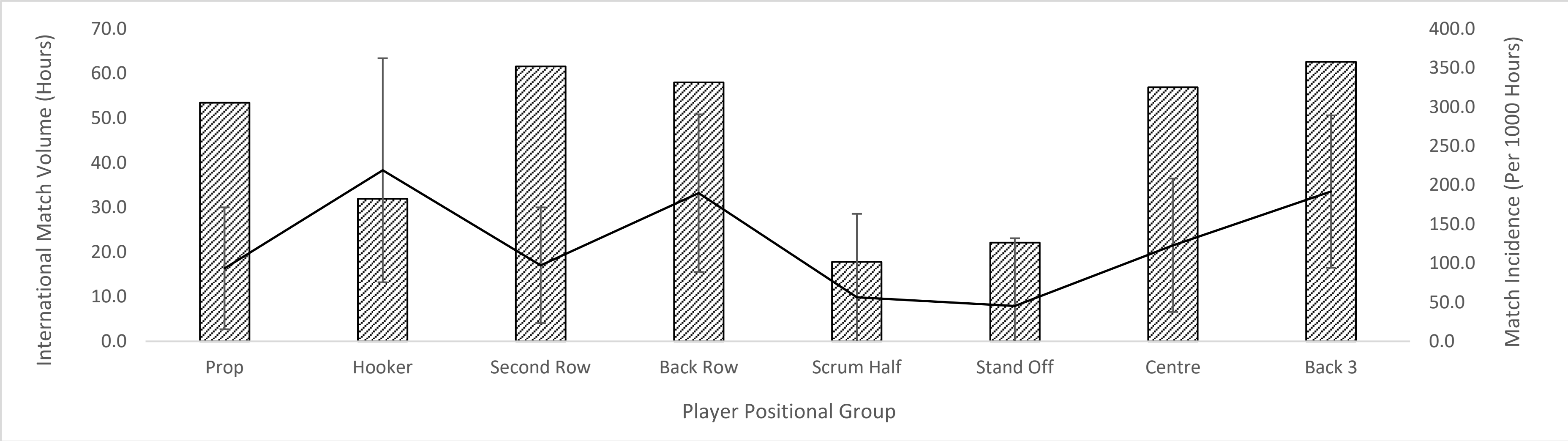
NOTE: International exposure in June represents the 2017/18 summer tour; white bars, Forwards match volume; grey bars, Backs match volume; solid line, Forwards match incidence; dashed line, Backs match incidence.

Incidence rates in relation to player positions were also assessed. Hookers had one of the lowest mean match exposures (0.84 hours per match) out of all positions, but reported the highest match incidence rate of 193.1 (95% CIs: 141.3–245) injuries per 1000 match hours (see Supplementary Figure 13). Props had a similar mean match exposure (0.79 hours per match), but had a much lower incidence rate of 117.8 (95% CIs: 88.0–147.5). Whereas Second Row players had a relatively high mean match exposure (1.09) but a low incidence rate (93.7 [95% CIs: 37.1–158.4] injuries per 1000 hours). Back Row players had the highest mean match exposure out of Forwards (1.11 hours), with an incidence rate of 132.9 [95% CIs: 23.8-173.9] injuries per 1000 hours of match play. Scrum Halves had a mean match exposure of 0.83 hours per match, and a corresponding low incidence rate of 102.2 injuries per 1000 match hours. The other positional Back groups had high mean match exposure values (Stand Off = 1.13; Centre = 1.12; Back 3 = 1.25), and relatively high incidence rates - particularly centres (Stand Off = 121.2 [95% CIs: 81.1–161.2] injuries per 1000 hours; Centre = 157.7 [95% CIs: 125.8-189.6] injuries per 1000 hours; Back 3 = 137.5 [95% CIs: 108.4-166.6] of match play, respectively). Supplementary Figure 14 shows the same positional groupings for international match exposure and match incidence, in which a similar pattern is reported.



Supplementary Figure 13: Mean match exposure and match incidence rates for SRU positional groupings over the 2017/18 and 2018/19 seasons.

NOTE: White bars, mean match volume; solid line, match incidence; error bars, 95% confidence intervals.

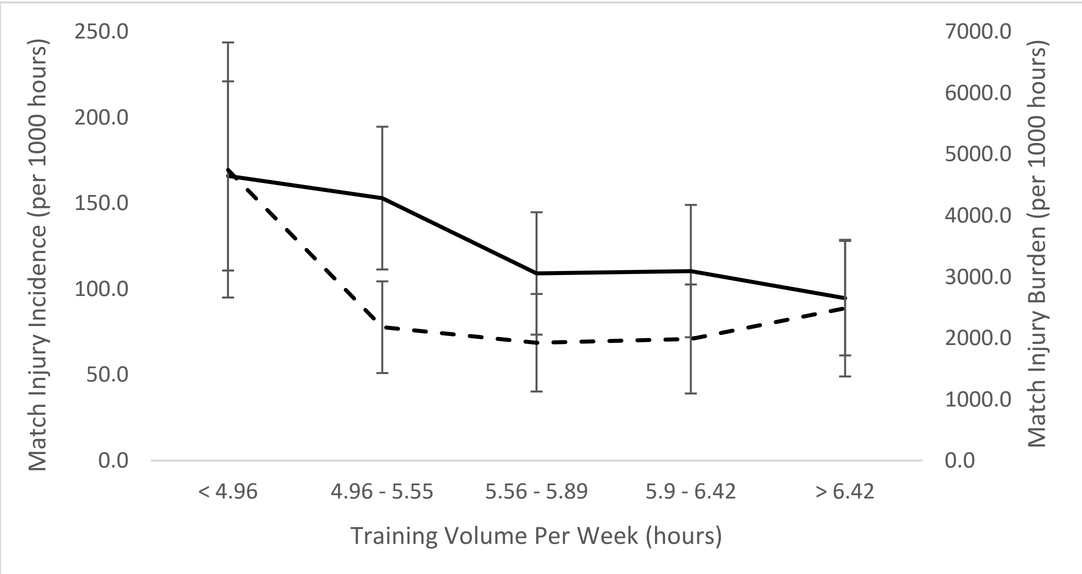


Supplementary Figure 14: Mean international match exposure and international match incidence rates for SRU positional groupings over the 2017/18 and 2018/19 seasons.

NOTE: Stripped bars, International match volume; solid line, International match incidence; error bars, 95% confidence intervals.

The Influence of Training Volume on Short Between-Match Recovery Periods and Injury

Players with the lowest weekly training volumes for short (6-day) between match periods, had the highest match incidence rate (166 [95% CIs: 110 - 221] injuries per 1000 hours). Players with the highest weekly training volumes for short (6-day) between match periods had the lowest incidence rates (94.7 [95% CIs: 61.3 - 128] injuries per 1000 hours). Match burden was highest for players with low weekly training volumes (4744.2 [95% CIs: 3296.8 – 6826.9] days absent per 1000 hours). Player match burden was lowest for players with an 'intermediate' weekly volume (5.56 – 5.89 hours per week) for short (6-day) between match periods (1923 [95% CIs: 1360 – 2719.3] injuries per 1000 match hours). Burden increased from intermediate volumes at a higher rate for players with high weekly volumes (> 6.42 hours per week; Burden = 2488.8 [95% CIs: 2718.4 – 3604.5] days absent per 1000 hours) (see Supplementary Figure 15).



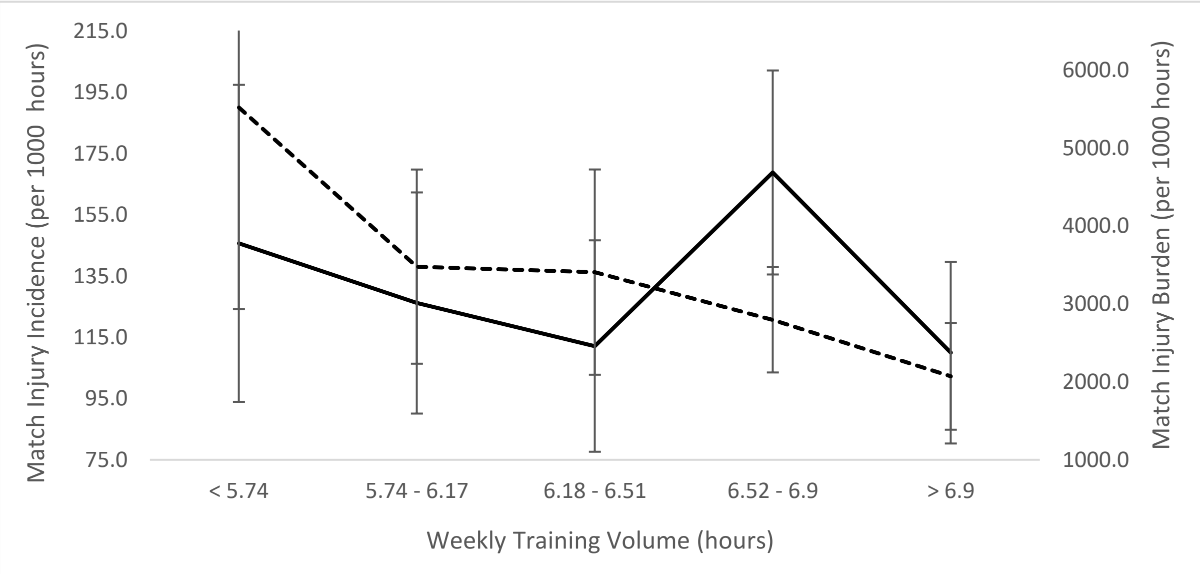
Supplementary Figure 15: The incidence and burden of match injuries as a function of mean weekly training volume leading up to Friday matches over the 2017/18 and 2018/19 seasons.

NOTE: Solid line, match incidence; dashed line, match burden; error bars, 95% confidence intervals.

The Influence of Training Volume on Saturday Match Injuries

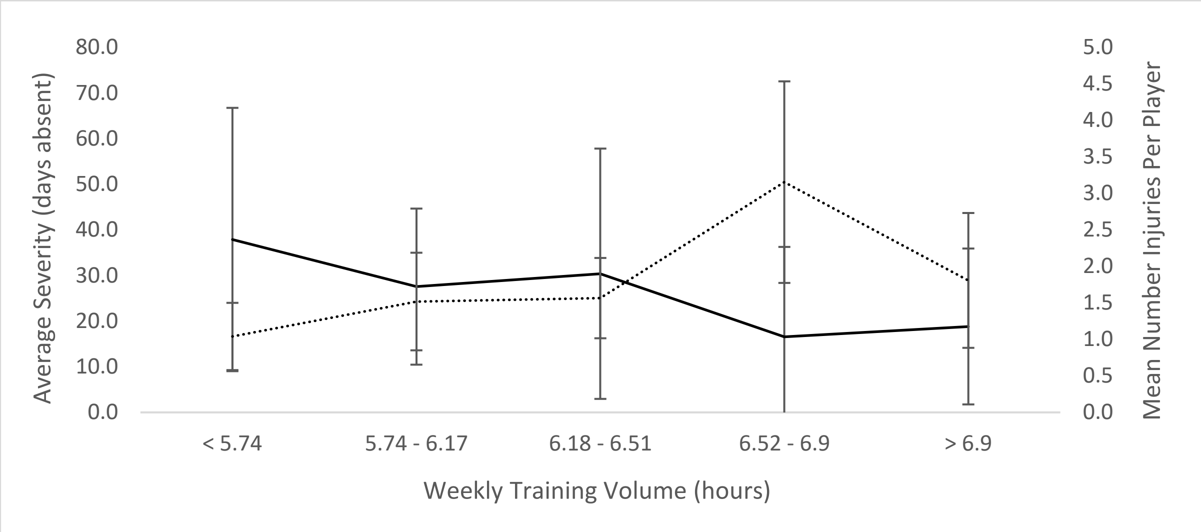
Players with 'intermediate high' weekly training volumes (6.52 – 6.9 hours per week) for long (7-day) between match periods had the highest match incidence rate (168.8 [95% CIs: 110 - 221] injuries per 1000 hours). Players with the highest weekly training volumes for long (7-day) between match periods (> 6.9 hours per week) had the lowest incidence rate (110 [95%

CIs: 93.9 – 197.4] injuries per 1000 hours). Players with 'low intermediate' weekly training volumes (6.2 - 6.51 hours per week) also had a low incidence rate (112.1 [77.6 – 146.7] injuries per 1000 hours). Low weekly volume (< 5.74 hours per week) was also associated with a high incidence rate (145.7 [93.9 -197.4] injuries per 1000 hours). Match burden was highest for players with low (< 5.74 hours) weekly training volumes (5519.2 [95% CIs: 3757.9 – 8106.2] days absent per 1000 hours). Player match burden decreased as training volume increased, and was thus lowest for players with a high weekly training volume (> 6.9 hours per week) or long between-match periods (2071.1 [95% CIs: 1556.1 – 2756.5] injuries per 1000 match hours) (see Supplementary Figure 16). The reduced burden for intermediate high volumes (6.52 – 6.9 hours per week) when there was a spike in incidence rate, suggests that although these players sustained a high number of injuries, the severity of these injuries was lower than for players with lower training volumes. Supplementary Figure 17 shows that players with 'high intermediate' (6.52 – 6.9 hours per week) weekly volumes reported the lowest average severity for match injuries (16.6 [95% CIs: -3.1 – 36.3] days absence per injury).



Supplementary Figure 16: The incidence and burden of match injuries as a function of mean weekly training volume leading up to Saturday matches over the 2017/18 and 2018/19 seasons.

NOTE: Solid line, match incidence; dashed line, match burden; error bars, 95% confidence intervals.

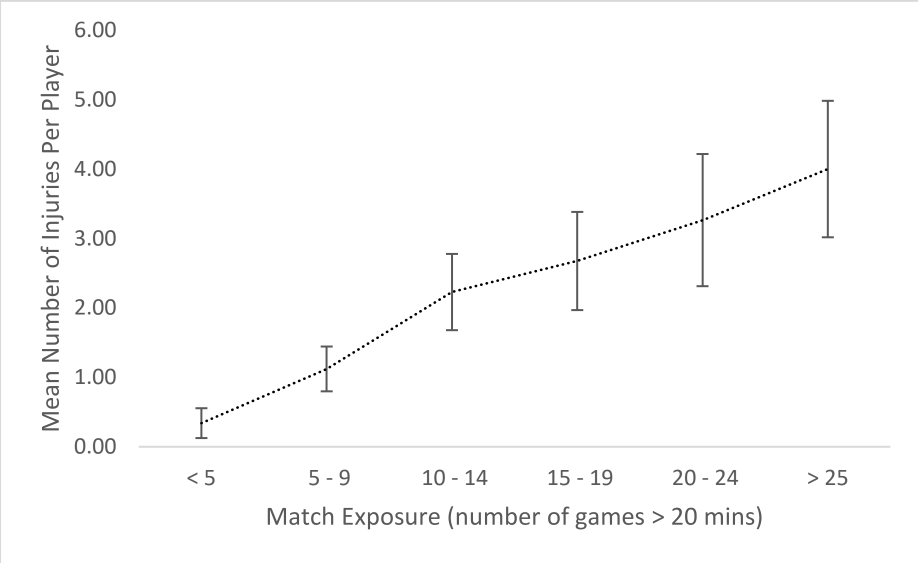


Supplementary Figure 17: Average severity and mean match injuries per player as a function of mean weekly training volume leading up to Saturday matches over the 2017/18 and 2018/19 seasons.

NOTE: Solid line, average severity of match injuries; dotted line, mean number of match injuries per player; error bars, 95% confidence intervals.

The Influence of Match Exposure on Injury Risk

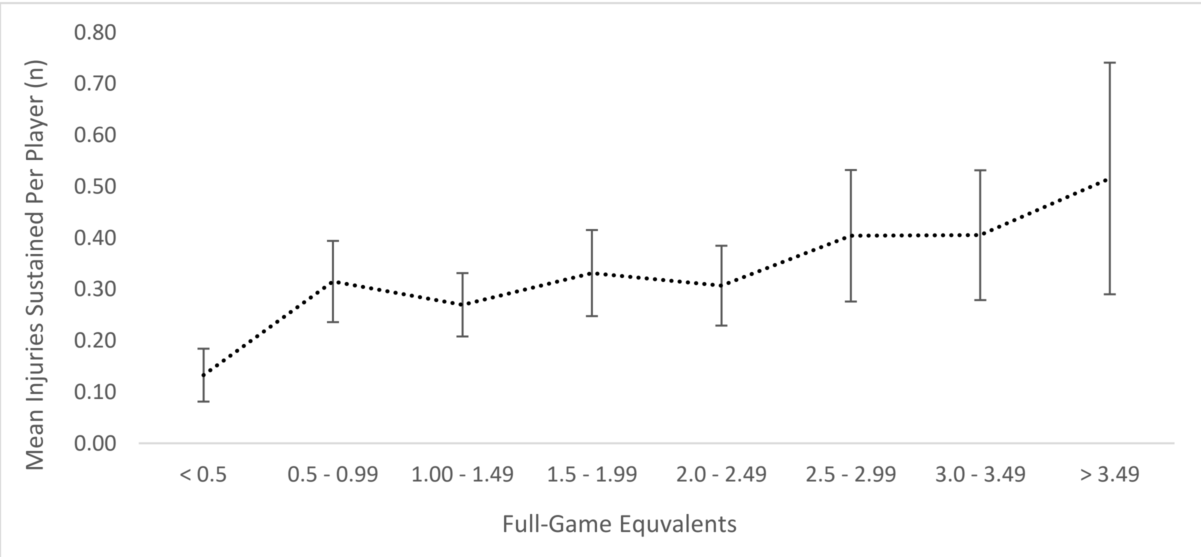
Players with the lowest match exposure sustained an average of 0.3 (95% CIs: 0.01 – 0.6) injuries per player, compared to 4 injuries (95% CIs: 2.5 – 4.5) per player for players exposed to > 25 matches (see Supplementary Figure 18). Together with the data presented in Chapter 3 (Figure 3.8), these findings highlight that the more games a player is exposed to, the more injuries they are likely to sustain, but that players with lower match exposure have a higher injury risk while competing in match play.



Supplementary Figure 18: The influence of 12-month match exposure on mean injuries sustained per player.

NOTE: Error bars, 95% confidence intervals.

For Full-Game Equivalents, players with the lowest match exposure sustained an average of 0.13 (95% CIs: 0.08 – 0.2) injuries per player, compared to 0.52 injuries (95% CIs: 0.3 – 0.7) per player for players exposed to > 3.49 FGEs in a 30-day period (see Supplementary Figure 19).



Supplementary Figure 19: Linear association between injury risk and 1-month match exposure, with 95% confidence intervals.

NOTE: Error bars, 95% confidence intervals.

APPENDIX F:

Quantifying the On-Pitch Demands of Elite Scottish Rugby Union Training and Match Play and its Association with Injury Risk (Chapter 4B) – Supplementary Data

Supplementary Table 1: Workload median splits for low and high chronic states for each external load variable. Players in a low chronic workload state were below the median value and players in a high chronic loading state were equal to or above the median value.

	Forwards				*Backs*			
Workload Variable	**Props**	**Hookers**	**Second Row**	**Back Row**	**Scrum Half**	**Stand Off**	**Centre**	**Back 3**
TD	11711	12290	13675	13669	15014	15446	14523	14460
HSR	562	918	789	1085	1853	1723	1787	1864
Acc > 2	382	474	474	515	627	775	691	647
Acc > 3	41	53	53	64	91	109	87	91
PlayerLoad™	1220	1273	1223	1280	1370	1525	1406	1320
Meters > 60%	513	603	611	622	857	925	913	898
Meters > 80%	35	50	37	46	61	75	69	90

NOTE: TD, total distance; HSR, high-speed running distance; acc > 2, acceleration meters above 2 $m \cdot s^{-2}$; acc > 3, acceleration meters above 3 $m \cdot s^{-2}$; meters > 60%, meters covered above 60% of maximum velocity; meters > 80%, meters covered above 80% of maximum velocity.

Positional Group Workload Categories

Props and Hookers

Supplementary Table 2: Classifications and boundaries for Front Row Forwards over 1-4 accumulated weeks and the absolute change from week-to-week.

		No. of Weeks Accumulated				
	Classification	1	2	3	4	Weekly Change
TD (m)	Very low	< 7457	< 15,724	< 24,218	< 31,994	< 1098
	Low	7457 - 10,123	15,724 - 20,636	24,218 - 30,699	31,994 - 41,001	1098 - 2584
	Intermediate low	10,124 - 12,449	20,637 - 24,232	30,700 - 35,577	41,002 - 47,336	2585 - 4043
	Intermediate high	12,450 - 14,590	24,234 - 27,462	35,578 - 40,425	47,337 - 53,045	4044 - 5935
	High	14,591 - 16,958	27,463 - 31,539	40,426 - 45,544	53,046 - 59,601	5936 - 8819
	Very high	> 16, 958	> 31,539	> 45,544	> 59,601	> 8819
HSR (m)	Very low	< 313	< 714	< 1159	< 1622	< 102
	Low	313 - 492	714 - 1030	1159 - 1561	1622 - 2137	102 - 213
	Intermediate low	493 - 662	1031 - 1333	1562 - 1967	2138 - 2619	214 - 328
	Intermediate high	663 - 912	1334 - 1736	1968 - 2572	2620 - 3301	329 - 505
	High	913 - 1249	1737 - 2374	2573 - 3434	3302 - 4421	506 - 828
	Very high	> 1249	> 2374	> 3434	> 4421	> 828
Accelerations (> 2 m·s^{-2})	Very low	< 238	< 519	< 792	< 1038	< 46
	Low	238 - 343	519 - 688	792 - 1042	1038 - 1382	46 - 102
	Intermediate low	343 - 428	689 - 834	1043 - 1255	1383 - 1661	103 - 166
	Intermediate high	429 - 516	835 - 1006	1256 - 1481	1662 - 1939	167 - 238
	High	517 - 664	1007 - 1242	1482 - 1793	1940 - 2290	239 - 361
	Very high	> 664	> 1242	> 1793	> 2290	> 361
Accelerations (> 3 m·s^{-2})	Very low	< 15.5	< 39	< 62	< 84	< 7
	Low	15.5 - 29.1	39 - 65	62 - 100	84 - 133	7 - 27
	Intermediate low	29.2 - 44.5	66 - 92	101 - 142	134 - 197	16 - 27
	Intermediate high	44.6 - 66.8	93 - 136	143 - 200	198 - 257	28 - 46
	High	66.9 - 106.3	137 - 203	201 - 293	258 - 383	47 - 78
	Very high	> 106.3	> 203	> 293	> 384	> 78
PlayerLoad™	Very low	< 746.3	< 1638	< 2602	< 3441	< 138
	Low	746.3 - 1106.6	1638 - 2186	2602 - 3354	3441 - 4449	138 - 283
	Intermediate low	1106.7 - 1356.1	2187 - 2608	3355 - 3833	4450 - 5118	284 - 469
	Intermediate high	1356.2 - 1599.1	2609 - 3000	3834 - 4383	5119 - 5742	470 - 690
	High	1599.2 - 1911.1	3010 - 3512	4384 - 5037	5743 - 6522	691 - 1035
	Very high	> 1911.1	> 3512	> 5038	> 6522	> 1035
Metres > 60% max (m)	Very low	< 151	< 421	< 710	< 974	< 66
	Low	151 - 383	421 - 807	710 - 1263	974 - 1683	66 - 165
	Intermediate low	384 - 559	808 - 1128	1264 - 1705	1684 - 2236	166 - 284
	Intermediate high	560 - 759	1129 - 1446	1706 - 2100	2237 - 2758	285 - 434
	High	760 - 1119	1447 - 2079	2102 - 2884	2759 - 3693	435 - 750
	Very high	> 1119	> 2079	> 2884	> 3697	>751
Metres > 80% max (m)	Very low	0	< 9	< 20	< 33	< 3
	Low	0.5 - 13.1	9 - 39	20 - 75	33 - 108	3 - 13
	Intermediate low	13.2 - 31.6	40 - 77	76 - 123	109 - 174	14 - 28
	Intermediate high	31.7 - 56.5	78 - 129	124 - 202	175 - 275	29 - 57
	High	56.6 - 122.1	130 - 253	203 - 399	276 - 575	58 - 125
	Very high	> 122.1	> 253	> 399	> 575	> 125

NOTE: TD, total distance in meters; HSR, High-speed running distance in meters; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Supplementary Table 3: Classifications and boundaries for Front Row Forwards: (ACWR) acute: chronic workload ratios overall, (low chronic) acute: chronic workload ratios combined with low chronic workload and (high chronic) acute: chronic workload ratios combined with high chronic workloads.

	Classification	ACWR	Low Chronic	High Chronic
TD (m)	Very low	< 0.65	< 0.80	< 0.57
	Low	0.65 - 0.89	0.80 - 1.04	0.57 - 0.75
	Intermediate low	0.90 - 1.06	1.05 - 1.28	0.76 - 0.93
	Intermediate high	1.07 - 1.26	1.29 - 1.55	0.94 - 1.06
	High	1.27 - 1.59	1.56 - 1.96	1.07 - 1.24
	Very high	> 1.59	> 1.96	> 1.24
HSR (m)	Very low	< 0.46	< 0.57	< 0.42
	Low	0.46 - 0.74	0.58 - 0.98	0.43 - 0.62
	Intermediate low	0.75 - 0.98	0.99 - 1.25	0.63 - 0.81
	Intermediate high	0.99 - 1.25	1.26 - 1.78	0.82 - 1.00
	High	1.26 - 1.87	1.79 - 2.57	1.01 - 1.29
	Very high	> 1.87	> 2.57	> 1.29
Accelerations (> 2 m·s^{-2})	Very low	< 0.59	< 0.74	< 0.55
	Low	0.59 - 0.84	0.74 -1.00	0.55 - 0.74
	Intermediate low	0.85 - 1.03	1.01 - 1.30	0.75 - 0.91
	Intermediate high	1.04 - 1.27	1.30 - 1.59	0.92 - 1.06
	High	1.28 - 1.70	1.60 - 2.12	1.07 - 1.29
	Very high	> 1.70	> 2.12	> 1.29
Accelerations (> 3 m·s^{-2})	Very low	< 0.37	< 0.42	< 0.34
	Low	0.37 - 0.65	0.42 - 0.82	0.34 - 0.58
	Intermediate low	0.66 - 0.97	0.83 - 1.22	0.59 - 0.78
	Intermediate high	0.98 - 1.33	1.23 - 1.81	0.79 - 1.09
	High	1.34 - 2.19	1.82 - 3.00	1.10 - 1.57
	Very high	> 2.19	> 3.00	> 1.57
PlayerLoad™	Very low	< 0.62	< 0.71	< 0.57
	Low	0.62 - 0.88	0.71 - 1.03	0.57 - 0.78
	Intermediate low	0.89 - 1.07	1.04 - 1.32	0.79 - 0.95
	Intermediate high	1.08 - 1.30	1.33 - 1.58	0.96 -1.11
	High	1.31 - 1.61	1.59 - 2.07	1.12 - 1.30
	Very high	> 1.61	> 2.07	> 1.30
Metres > 60% max (m)	Very low	< 0.31	< 0.11	< 0.39
	Low	0.31 - 0.66	0.12 - 0.76	0.39 - 0.64
	Intermediate low	0.67 - 0.96	0.77 - 1.17	0.65 - 0.85
	Intermediate high	0.97 - 1.28	1.18 - 1.76	0.86 - 1.06
	High	1.29 - 1.95	1.77 - 2.80	1.07 - 1.39
	Very high	> 1.95	> 2.80	> 1.39
Metres > 80% max (m)	Very low	0		< 0.07
	Low	0.01 - 0.15	0	0.07 - 0.26
	Intermediate low	0.16 - 0.54	0.02 - 0.52	0.27 - 0.55
	Intermediate high	0.55 - 1.10	0.53 - 1.55	0.56 - 0.96
	High	1.11 - 2.36	1.56 - 3.91	0.97 - 1.61
	Very high	> 2.36	> 3.91	> 1.61

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Second and Back Row

Supplementary Table 4: Classifications and boundaries for the Second and Back Row Forwards over 1-4 accumulated weeks and the absolute change from week-to-week.

	Classification	No. of Weeks Accumulated 1	2	3	4	Weekly Change
TD (m)	Very low	< 8129	< 17,284	< 26, 288	< 35, 446	< 1574
	Low	8129 - 11,612	17,284 - 23, 263	26,288 - 34,562	35, 446 - 46,196	1574 - 3125
	Intermediate low	11,613 - 14,117	23,264 - 27,415	34,563 - 40, 57	46,197 - 53,500	3126 - 4756
	Intermediate high	14,118 - 16,759	27,416 - 31,467	40,858 - 46,295	53,501 - 60,641	4757 - 7091
	High	16,760 - 20,202	31,462 - 37,128	46,296 - 52,830	60,642 - 69,256	7092 - 10,760
	Very high	> 20, 202	> 37,128	> 52, 830	> 69, 256	> 10,760
HSR (m)	Very low	< 519	< 1208	< 1785	< 2442	< 168
	Low	519 - 796	1208 - 1649	1785 - 2501	2442 - 3298	168 - 301
	Intermediate low	797 - 1034	1650 - 2046	2502 - 3061	3299 - 4082	302 - 483
	Intermediate high	1035 - 1318	2047 - 2540	3062 - 3643	4083 - 4760	484 - 726
	High	1319 - 1786	2541 - 3227	3644 - 4616	4761 - 6041	727 - 1148
	Very high	> 1786	> 3227	> 4616	> 6041	> 1148
Accelerations (> 2 m·s^{-2})	Very low	< 311	< 680	< 999	< 1324	< 59
	Low	311 - 442	680 - 887	999 - 1321	1324 - 1758	59 - 122
	Intermediate low	443 - 543	888 - 1050	1322 - 1567	1759 - 2060	123 - 210
	Intermediate high	544 - 646	1051 - 1226	1568 - 1800	2061 - 2336	211 - 313
	High	646 - 797	1227 - 1427	1801 - 2096	2337 - 2725	314 - 460
	Very high	> 797	> 1427	> 2096	> 2725	> 460
Accelerations (> 3 m·s^{-2})	Very low	< 25.1	< 59	< 93	< 123	< 10
	Low	25.1 - 42.2	59 - 89	93 - 137	123 - 188	10 - 20
	Intermediate low	42.3 - 60.2	90 -130	138 - 193	189 - 253	21 - 34
	Intermediate high	60.3 - 86.9	131 - 169	194 - 252	254 - 331	35 - 54
	High	87.0 - 128.4	170 - 229	253 - 339	332 - 431	55 - 92
	Very high	> 128.4	> 229	> 339	> 431	> 92
PlayerLoad™	Very low	< 740	< 1618	< 2443	< 3175	< 159
	Low	740 - 1123	1618 - 2204	2443 - 3318	3175 - 4374	159 - 327
	Intermediate low	1124 - 1383	2205 - 2653	3319 - 3959	4378 - 5201	328 - 501
	Intermediate high	1384 - 1704	2654 - 3152	3960 - 4601	5202 - 5976	502 - 771
	High	1705 - 2087	3153 - 3778	4602 - 5424	5978 - 7044	772 - 1154
	Very high	> 2087	> 3779	> 5425	> 7045	> 1154
Metres > 60% max (m)	Very low	< 192	< 501	< 772	< 1036	< 85
	Low	192 - 445	501 - 976	772 - 1457	1036 - 1932	85 - 203
	Intermediate low	446 - 682	977 - 1349	1458 - 2008	1933 - 2642	204 - 350
	Intermediate high	683 - 917	1350 - 1731	2009 - 2547	2643 - 3315	351 - 544
	High	918 - 1265	1732 - 2302	2548 - 3288	3316 - 4274	545 - 850
	Very high	> 1265	> 2302	> 3288	> 4274	> 851
Metres > 80% max (m)	Very low	0	< 7	< 20	< 38	< 2
	Low	0.5 - 16.3	7 - 53	20 - 84	38 - 117	2 - 18
	Intermediate low	16.4 - 40.5	54 - 98	85 - 150	118 - 210	19 - 36
	Intermediate high	40.6 - 70.8	99 - 152	151 - 237	211 - 333	37 - 66
	High	70.9 - 133.2	153 - 269	238 - 406	334 - 524	67 - 130
	Very high	> 133.2	> 269	> 406	> 524	> 130

NOTE: TD, total distance in meters; HSR, High-speed running distance in meters; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Supplementary Table 5: Classifications and boundaries for Second and Back Row Forwards: (ACWR) acute: chronic workload ratios overall, (low chronic) acute: chronic workload ratios combined with low chronic workload and (high chronic) acute: chronic workload ratios combined with high chronic workloads.

	Classification	ACWR	Low Chronic	High Chronic
TD (m)	Very low	< 0.62	< 0.81	< 0.54
	Low	0.62 - 0.90	0.81 - 1.05	0.54 - 0.75
	Intermediate low	0.91 - 1.07	1.06 - 1.33	0.76 - 0.93
	Intermediate high	1.08 - 1.30	1.34 - 1.62	0.94 - 1.08
	High	1.31 - 1.67	1.62 - 2.05	1.09 - 1.28
	Very high	> 1.67	> 2.05	> 1.28
HSR (m)	Very low	< 0.51	< 0.66	< 0.47
	Low	0.51 - 0.77	0.66 - 0.98	0.47 - 0.65
	Intermediate low	0.78 - 0.99	0.99 - 1.26	0.66 - 0.84
	Intermediate high	1.00 - 1.28	1.27 - 1.62	0.85 - 1.01
	High	1.29 - 1.80	1.63 - 2.56	1.02 - 1.35
	Very high	> 1.80	> 2.56	> 1.35
Accelerations (> 2 m·s^{-2})	Very low	< 0.59	< 0.80	< 0.54
	Low	0.59 - 0.87	0.80 - 1.04	0.54 - 0.76
	Intermediate low	0.88 - 1.04	1.05 - 1.38	0.77 - 0.92
	Intermediate high	1.05 - 1.28	1.39 - 1.73	0.93 - 1.07
	High	1.29 - 1.75	1.74 - 2.30	1.08 - 1.27
	Very high	> 1.75	> 2.30	> 1.27
Accelerations (> 3 m·s^{-2})	Very low	< 0.41	< 0.52	< 0.38
	Low	0.41 - 0.72	0.52 - 0.96	0.38 - 0.61
	Intermediate low	0.73 - 1.00	0.97 - 1.24	0.62 - 0.84
	Intermediate high	1.01 - 1.34	1.25 - 1.79	0.85 - 1.10
	High	1.35 - 201	1.80 - 3.13	1.11 - 1.46
	Very high	> 2.01	> 3.13	> 1.46
PlayerLoad™	Very low	< 0.59	< 0.70	< 0.56
	Low	0.59 - 0.87	0.70 - 1.00	0.56 - 0.79
	Intermediate low	0.88 - 1.09	1.01 - 1.35	0.80 - 0.97
	Intermediate high	1.10 - 1.34	1.36 - 1.69	0.98 - 1.16
	High	1.35 - 1.73	1.7	1.17 - 1.37
	Very high	> 1.73	> 2.31	> 1.38
Metres > 60% max (m)	Very low	< 0.30	0	< 0.43
	Low	0.30 - 0.67	0.01 - 0.74	0.43 - 0.64
	Intermediate low	0.68 - 0.95	0.75 - 1.18	0.65 - 0.85
	Intermediate high	0.96 - 1.25	1.19 - 1.78	0.86 - 1.04
	High	1.26 - 1.91	1.78 - 2.92	1.05 - 1.38
	Very high	> 1.91	> 2.92	> 1.38
Metres > 80% max (m)	Very low	0		< 0.12
	Low	0.01 - 0.14	0	0.12 - 0.36
	Intermediate low	0.15 - 0.55	0.02 - 0.15	0.37 - 0.64
	Intermediate high	0.56 - 1.06	0.16 - 1.22	0.65 - 1.00
	High	1.07 - 2.35	1.23 - 4.36	1.01 - 1.77
	Very high	> 2.36	> 4.36	> 1.77

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Halfbacks

Supplementary Table 6: Classifications and boundaries for Halfbacks over 1-4 accumulated weeks and the absolute change from week-to-week.

	Classification	No. of Weeks Accumulated 1	2	3	4	Weekly Change
TD (m)	Very low	< 9733	< 20, 379	< 30,407	< 40,327	< 1532
	Low	9733 - 13,276	20,279 - 26,270	30,407 - 39,497	40,327 - 52,502	1532 - 3233
	Intermediate low	13,276 - 15,899	26,271 - 31,150	39,498 - 45,730	52,503 - 60,602	3234 - 4963
	Intermediate high	15,900 - 19,016	31,151 - 36,275	45,731 - 53,335	60,603 - 69,664	4964 - 7163
	High	19,017 - 22,698	36,276 - 42,486	53,335 - 61,213	69,665 - 80,303	7164 - 10,869
	Very high	> 22,698	> 42,486	> 61,213	> 80,303	> 10,869
HSR (m)	Very low	< 1171	< 2444	< 3790	< 5200	< 187
	Low	1171 - 1560	2444 - 3186	3790 - 4819	5200 - 6297	187 - 420
	Intermediate low	1561 - 1892	3187 - 3698	4820 - 5412	6298 - 7127	421 - 685
	Intermediate high	1893 - 2180	3699 - 4177	5413 - 6027	7128 - 7948	686 - 957
	High	2181 - 2679	4178 - 4917	6028 - 7263	7963 - 9377	958 - 1442
	Very high	> 2679	> 4917	> 7263	> 9377	> 1442
Accelerations (> 2 m·s^{-2})	Very low	< 433	< 936	< 1366	< 1870	< 72
	Low	433 - 581	936 - 1185	1366 - 1805	1870 - 2390	72 - 160
	Intermediate low	582 - 711	1186 - 1394	1806 - 2114	2391 - 2742	161 - 245
	Intermediate high	712 - 851	1395 - 1602	2115 - 2360	2743 - 3125	246 - 354
	High	852 - 1011	1603 - 1887	2361 - 2704	3126 - 3538	355 - 513
	Very high	> 1011	> 1887	> 2704	> 3538	> 513
Accelerations (> 3 m·s^{-2})	Very low	< 47.3	< 104	< 169	< 227	< 15
	Low	47.3 - 71.6	104 - 149	169 - 227	227 - 302	15 - 29
	Intermediate low	71.7 - 94.2	150 - 194	228 - 297	303 - 393	30 - 47
	Intermediate high	94.3 - 124.3	195 - 246	298 - 373	394 - 493	48 - 72
	High	124.4 - 179.1	247 - 327	374 - 474	494 - 604	73 - 112
	Very high	> 179.1	> 328	> 474	> 605	> 112
PlayerLoad™	Very low	< 949	< 2052	< 3186	< 4323	< 170
	Low	949 - 1309	2052 - 2565	3186 - 3861	4323 - 5155	1.70 - 325
	Intermediate low	1310 - 1598	2566 - 2985	3862 - 4394	5156 - 5839	326 - 530
	Intermediate high	1599 - 1861	2986 - 3428	4395 - 5086	5840 - 6598	531 - 754
	High	1862 - 2269	3429 - 4249	5087 - 6034	6599 - 7690	755 - 1130
	Very high	> 2262	> 4249	> 6034	> 7690	> 1130
Metres > 60% max (m)	Very low	< 458	< 981	< 1531	< 2015	< 135
	Low	458 - 723	981 - 1472	1531 - 2271	2015 - 3007	135 - 267
	Intermediate low	724 - 933	1473 - 1876	2272 - 2737	3008 - 3579	268 - 458
	Intermediate high	934 - 1191	1877 - 2314	2738 - 3343	3580 - 4431	459 - 632
	High	1192 - 1660	2315 - 3044	3344 - 4454	4432 - 5696	633 - 960
	Very high	> 1660	> 3044	> 4454	> 5696	> 960
Metres > 80% max (m)	Very low	< 5	< 25	< 61	< 85	< 9
	Low	5 - 29	25 - 81	61 - 139	85 - 194	9 - 26
	Intermediate low	30 - 63	82 - 141	140 - 216	195 - 306	27 - 53
	Intermediate high	64 - 104	142 - 218	217 - 335	307 - 460	54 - 88
	High	105 - 202	219 - 402	336 - 601	461 - 794	89 - 187
	Very high	> 202	> 402	> 601	> 794	> 187

NOTE: TD, total distance in meters; HSR, High-speed running distance in meters; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Supplementary Table 7: Classifications and boundaries for Halfbacks: (ACWR) acute: chronic workload ratios overall, (low chronic) acute: chronic workload ratios combined with low chronic workload and (high chronic) acute: chronic workload ratios combined with high chronic workloads.

	Classification	ACWR	Low Chronic	High Chronic
TD (m)	Very low	< 0.68	< 0.79	< 0.61
	Low	0.68 - 0.89	0.79 - 1.01	0.61 - 0.79
	Intermediate low	0.90 - 1.05	1.02 - 1.24	0.80 - 0.94
	Intermediate high	1.06 - 1.24	1.25 -1.47	0.95 - 1.06
	High	1.25 - 1.55	1.48 - 1.85	1.07 - 1.24
	Very high	> 1.55	> 1.85	> 1.24
HSR (m)	Very low	< 0.61	< 0.70	< 0.58
	Low	0.61 - 0.86	0.70 - 1.00	0.58 - 0.75
	Intermediate low	0.87 - 1.02	1.01 - 1.23	0.76 - 0.93
	Intermediate high	1.03 - 1.24	1.24 - 1.47	0.94 - 1.04
	High	1.25 - 1.58	1.48 - 1.97	1.05 - 1.27
	Very high	> 1.58	> 1.97	> 1.27
Accelerations (> 2 m·s^{-2})	Very low	< 0.64	< 0.78	< 0.60
	Low	0.64 - 0.89	0.78 - 1.00	0.61 - 0.78
	Intermediate low	0.90 - 1.04	1.01 - 1.27	0.79 - 0.94
	Intermediate high	1.05 - 1.28	1.28 - 1.46	0.95 - 1.06
	High	1.29 - 1.54	1.47 - 1.98	1.07 - 1.30
	Very high	> 1.54	> 1.98	> 1.31
Accelerations (> 3 m·s^{-2})	Very low	< 0.48	< 0.59	< 0.45
	Low	0.48 - 0.75	0.59 - 0.92	0.45 - 0.64
	Intermediate low	0.76 - 1.00	0.93 - 1.23	0.65 - 0.85
	Intermediate high	1.01 - 1.29	1.24 - 1.65	0.86 - 1.08
	High	1.30 - 1.80	1.66 - 2.39	1.09 - 1.39
	Very high	> 1.80	> 2.39	> 1.39
PlayerLoad™	Very low	< 0.68	< 0.72	< 0.63
	Low	0.68 - 0.88	0.73 - 1.03	0.63 - 0.77
	Intermediate low	0.89 - 1.07	1.04 - 1.26	0.78 - 0.95
	Intermediate high	1.08 - 1.27	1.27 - 1.46	0.96 - 1.09
	High	1.28 - 1.54	1.47 - 1.88	1.10 - 1.33
	Very high	> 1.54	> 1.88	> 1.34
Metres > 60% max (m)	Very low	< 0.50	< 0.51	< 0.51
	Low	0.50 - 0.77	0.51 - 0.93	0.51 - 0.72
	Intermediate low	0.78 - 1.00	0.94 - 1.21	0.73 - 0.90
	Intermediate high	1.01 - 1.26	1.22 - 1.58	0.91 - 1.08
	High	1.27 - 1.71	1.59 - 2.55	1.09 - 1.34
	Very high	> 1.71	> 2.55	> 1.34
Metres > 80% max (m)	Very low	< 0.03	0	< 0.17
	Low	0.03 - 0.33	0.01 - 0.26	0.17 - 0.35
	Intermediate low	0.34 - 0.67	0.22 - 0.88	0.36 - 0.57
	Intermediate high	0.68 - 1.16	0.92 - 1.98	0.58 - 0.95
	High	1.17 - 2.53	1.99 - 4.40	0.96 - 1.51
	Very high	> 2.53	> 4.40	> 1.51

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Centres

Supplementary Table 8: Classifications and boundaries for Centre positional Backs over 1-4 accumulated weeks and the absolute change from week-to-week.

		No. of Weeks Accumulated				
	Classification	**1**	**2**	**3**	**4**	**Weekly Change**
TD (m)	Very low	< 8532	< 18,085	< 27,003	< 34,256	< 1821
	Low	8532 - 12,308	18,085 - 24,721	27,003 - 37,836	34,256 - 49,042	1821 - 3586
	Intermediate low	12,309 - 15,848	24,722 - 30,412	37,837 - 44,297	49,043 - 58,570	3587 - 5891
	Intermediate high	15,849 - 18 995	30,413 - 35,433	44,298 - 51,926	58,571 - 66,573	5892 - 8371
	High	18,996 - 22,448	35,434 - 41,777	51,927 - 60,175	66,574 - 77,723	8372 - 12, 100
	Very high	> 22, 448	> 41, 777	> 60,175	> 77,723	> 12, 100
HSR (m)	Very low	< 1084	< 2404	< 3703	< 4963	< 242
	Low	1084 - 1620	2404 - 3289	3703 - 4819	4963 - 6440	242 - 495
	Intermediate low	1621 - 2057	3290 - 3952	4820 - 5692	6441 - 7498	496 - 762
	Intermediate high	2058 - 2399	3953 - 4517	5693 - 6479	7499 - 8400	763 - 1167
	High	2400 - 2846	4518 - 5251	6480 - 7456	8401 - 9537	1168 - 1633
	Very high	> 2846	> 5251	> 7456	> 9537	> 1633
Accelerations (> 2 m·s^{-2})	Very low	< 412	< 828	< 1283	< 1773	< 112
	Low	412 - 608	828 - 1257	1283 - 1816	1773 - 2415	112 - 213
	Intermediate low	609 - 772	1258 - 1553	1817 - 2224	2416 - 2890	214 - 322
	Intermediate high	773 - 995	1554 - 1761	2225 - 2620	2891 - 3373	323 - 455
	High	996 - 1171	1762 - 2098	2621 - 3023	3374 - 3911	456 - 626
	Very high	> 1171	> 2098	> 3023	> 3911	> 626
Accelerations (> 3 m·s^{-2})	Very low	< 48	< 103	< 159	< 213	< 16
	Low	48 - 73	103 - 153	159 - 234	213 - 310	16 - 33
	Intermediate low	73 - 97	154 - 195	234 - 287	311 - 382	34 - 50
	Intermediate high	98 - 128	196 - 256	288 - 376	383 - 496	51 - 77
	High	128 - 188	257 - 345	377 - 484	497 - 636	78 - 122
	Very high	> 188	> 345	> 484	> 636	> 122
PlayerLoad™	Very low	< 830	< 1753	< 2622	< 3551	< 198
	Low	830 - 1250	1753 - 2539	2622 - 3645	3551 - 4965	198 - 374
	Intermediate low	1251 - 1614	2540 - 3038	3646 - 4545	4966 - 5830	375 - 638
	Intermediate high	1615 - 1930	3039 - 3618	4546 - 5246	5831 - 6780	639 - 854
	High	1931 - 2332	3619 - 4272	5247 - 6023	6781 - 7909	855 - 1224
	Very high	> 2332	> 4272	> 6023	> 7909	> 1224
Metres > 60% max (m)	Very low	< 429	< 1005	< 1595	< 2070	< 158
	Low	429 - 789	1005 - 1644	1595 - 2346	2070 - 3108	158 - 315
	Intermediate low	790 - 1064	1645 - 2056	2347 - 2967	3109 - 3931	316 - 515
	Intermediate high	1065 - 1307	2057 - 2473	2968 - 3589	3932 - 4624	516 - 716
	High	1308 - 1658	2474 - 2998	3590 - 4319	4625 - 5643	717 - 1003
	Very high	> 1658	> 2998	> 4319	> 5643	> 1003
Metres > 80% max (m)	Very low	< 8	< 40	< 90	< 123	< 10
	Low	08 - 41	40 - 107	90 - 173	123 - 234	10 - 32
	Intermediate low	42 - 76	108 - 163	174 - 242	235 - 314	33 - 65
	Intermediate high	77 - 121	164 - 235	243 - 343	315 - 457	66 - 100
	High	122 - 193	236 - 351	344 - 499	458 - 650	101 - 170
	Very high	> 193	> 351	> 499	> 650	> 170

NOTE: TD, total distance in meters; HSR, High-speed running distance in meters; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Supplementary Table 9: Classifications and boundaries for Centre Backs: (ACWR) acute: chronic workload ratios overall, (low chronic) acute: chronic workload ratios combined with low chronic workload and (high chronic) acute: chronic workload ratios combined with high chronic workloads.

			Median Split	
	Classification	**ACWR**	**Low Chronic**	**High Chronic**
TD (m)	Very low	< 0.62	< 0.81	< 0.53
	Low	0.62 - 0.91	0.81 - 1.07	0.53 - 0.76
	Intermediate low	0.92 - 1.09	1.08 - 1.39	0.77 - 0.96
	Intermediate high	1.10 - 1.35	1.40 - 1.70	0.97 - 1.11
	High	1.36 - 1.73	1.71 - 2.22	1.12 - 1.31
	Very high	> 1.73	> 2.22	> 1.31
HSR (m)	Very low	< 0.62	< 0.76	< 0.51
	Low	0.62 - 0.88	0.76 - 1.08	0.51 - 0.73
	Intermediate low	0.89 - 1.09	1.09 - 1.38	0.74 - 0.94
	Intermediate high	1.10 - 1.36	1.39 - 1.72	0.95 - 1.10
	High	1.37 - 1.75	1.73 - 2.23	1.11 - 1.30
	Very high	> 1.75	> 2.23	> 1.31
Accelerations (> 2 m·s^{-2})	Very low	< 0.58	< 0.81	< 0.53
	Low	0.58 - 0.87	0.81 - 1.04	0.53 - 0.75
	Intermediate low	0.88 - 1.08	1.05 - 1.39	0.76 - 0.93
	Intermediate high	1.09 - 1.38	1.40 - 1.86	0.94 - 1.12
	High	1.39 - 1.92	1.87 - 2.83	1.13 - 1.36
	Very high	> 1.92	> 2.83	> 1.36
Accelerations (> 3 m·s^{-2})	Very low	< 0.48	< 0.65	< 0.45
	Low	0.48 - 0.77	0.65 - 1.00	0.45 - 0.65
	Intermediate low	0.78 - 1.01	1.01 - 1.41	0.66 - 0.86
	Intermediate high	1.02 - 1.42	1.42 - 1.88	0.87 - 1.09
	High	1.43 - 2.19	1.89 - 3.31	1.10 - 1.51
	Very high	> 2.19	> 3.31	> 1.51
PlayerLoad™	Very low	< 0.61	< 0.71	< 0.56
	Low	0.62 - 0.89	0.71 - 1.05	0.56 - 0.78
	Intermediate low	0.90 - 1.08	1.06 - 1.44	0.79 - 0.97
	Intermediate high	1.09 - 1.36	1.45 - 1.78	0.98 - 1.14
	High	1.37 - 1.79	1.79 - 2.48	1.15 - 1.36
	Very high	> 1.79	> 2.49	> 1.36
Metres > 60% max (m)	Very low	< 0.49	< 0.36	< 0.53
	Low	0.49 - 0.82	0.36 - 1.00	0.53 - 0.73
	Intermediate low	0.83 - 1.04	1.01 - 1.43	0.74 - 0.91
	Intermediate high	1.05 - 1.37	1.44 - 1.97	0.92 - 1.11
	High	1.38 - 1.97	1.98 - 3.23	1.12 - 1.40
	Very high	> 1.97	> 3.23	> 1.40
Metres > 80% max (m)	Very low	0	0	< 0.17
	Low	0.01 - 0.39	0.01 - 0.14	0.17 - 0.42
	Intermediate low	0.40 - 0.75	0.15 - 0.92	0.43 - 0.69
	Intermediate high	0.75 - 1.20	0.93 - 2.06	0.70 - 1.01
	High	1.21 - 2.44	2.07 - 4.64	1.02 - 1.55
	Very high	> 2.44	> 4.64	> 1.55

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Back Three

Supplementary Table 10: Classifications and boundaries for the Back 3 positional Backs over 1-4 accumulated weeks and the absolute change from week-to-week.

		No. of Weeks Accumulated				
	Classification	**1**	**2**	**3**	**4**	**Weekly Change**
TD (m)	Very low	< 8162	< 17,634	< 26,783	< 34,986	< 1672
	Low	8162 - 12,218	17,634 - 24,074	26, 783 - 37,245	34, 986 - 48,695	1672 - 3409
	Intermediate low	12,219 - 15,623	24,075 - 30,006	37, 246 - 44,318	48, 696 - 58,587	3410 - 5420
	Intermediate high	15,624 - 18,476	30,007 - 35,168	44, 319 - 51,416	58, 588 - 66,848	5421 - 8277
	High	18,477 - 22,567	35,169 - 41,247	51, 417 - 58,935	66, 849 - 77,571	8278 - 12,454
	Very high	> 22,567	> 41,247	> 58,935	> 77,571	> 12,454
HSR (m)	Very low	< 1074	< 2361	< 3419	< 4626	< 249
	Low	1074 - 1588	2361 - 3238	3419 - 4829	4626 - 6428	249 - 495
	Intermediate low	1589 - 1986	3239 - 3944	4830 - 5895	6429 - 7704	496 - 835
	Intermediate high	1987 - 2423	3945 - 4656	5896 - 6754	7705 - 8886	836 - 1194
	High	2424 - 2990	4657 - 5451	6755 - 7885	8887 - 10, 226	1195 - 1711
	Very high	> 2990	> 5451	> 7885	> 10, 266	> 1711
Accelerations (> 2 m·s^{-2})	Very low	< 341	< 769	< 1186	< 1531	< 96
	Low	341 - 549	769 - 1113	1186 - 1674	1531 - 2186	96 - 180
	Intermediate low	550 - 680	1114 - 1376	1675 - 2048	2187 - 2667	181 - 304
	Intermediate high	681 - 862	1377 - 1620	2049 - 2377	2668 - 3081	305 - 409
	High	863 - 1060	1621 - 1914	2378 - 2758	3082 - 3588	410 - 619
	Very high	> 1060	> 1914	> 2758	> 3588	> 619
Accelerations (> 3 m·s^{-2})	Very low	< 39.7	< 94	< 150	< 194	< 15
	Low	39.8 - 69.8	94 - 152	150 - 229	194 - 291	15 - 31
	Intermediate low	69.9 - 98.3	153 - 198	230 - 293	292 - 391	32 - 53
	Intermediate high	98.4 - 131.4	199 - 249	294 - 368	392 - 481	54 - 78
	High	131.5 - 176.4	250 - 327	369 - 471	482 - 603	79 - 116
	Very high	> 176.4	> 327	> 471	> 603	> 116
PlayerLoad™	Very low	< 726	< 1616	< 2450	< 3126	< 167
	Low	726 - 1126	1616 - 2305	2450 - 3405	3126 - 4499	167 - 345
	Intermediate low	1127 - 1460	2306 - 2797	3406 - 4115	4500 - 5479	346 - 540
	Intermediate high	1461 - 1751	2798 - 3244	4116 - 4811	5480 - 6295	541 - 802
	High	1752 - 2120	3245 - 3925	4812 - 5496	6296 - 7163	803 - 1161
	Very high	> 2120	> 3925	> 5496	> 7163	> 1161
Metres > 60% max (m)	Very low	< 415	< 911	< 1411	< 1908	< 119
	Low	415 - 700	911 - 1522	1411 - 2271	1908 - 3004	119 - 280
	Intermediate low	701 - 1003	1523 - 1960	2272 - 2984	3005 - 3962	281 - 464
	Intermediate high	1004 - 1270	1961 - 2388	2985 - 3616	3962 - 4643	465 - 691
	High	1271 - 1643	2389 - 3067	3617 - 4344	4643 - 5583	692 - 1077
	Very high	> 1643	> 3067	> 4344	> 5583	> 1077
Metres > 80% max (m)	Very low	< 10	< 54	< 98	< 131	< 12
	Low	10 - 48	54 - 127	98 - 196	131 - 268	12 - 40
	Intermediate low	48 - 90	128 - 207	197 - 317	269 - 423	41 - 74
	Intermediate high	91 - 143	208 - 296	318 - 462	424 - 623	75 - 120
	High	144 - 235	297 - 498	463 - 759	624 - 993	121 - 224
	Very high	> 235	> 498	> 759	> 993	> 224

NOTE: TD, total distance in meters; HSR, High-speed running distance in meters; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Supplementary Table 11: Classifications and boundaries for the Back 3: (ACWR) acute: chronic workload ratios overall, (low chronic) acute: chronic workload ratios combined with low chronic workload and (high chronic) acute: chronic workload ratios combined with high chronic workloads.

			Median Split	
	Classification	**ACWR**	**Low Chronic**	**High Chronic**
TD (m)	Very low	< 0.60	< 0.70	< 0.54
	Low	0.60 - 0.88	0.71 - 1.02	0.54 - 0.77
	Intermediate low	0.89 - 1.06	1.03 - 1.36	0.78 - 0.94
	Intermediate high	1.07 - 1.34	1.37 - 1.63	0.95 - 1.08
	High	1.35 - 1.70	1.64 - 2.25	1.09 - 1.31
	Very high	> 1.70	> 2.25	> 1.31
HSR (m)	Very low	< 0.60	< 0.66	< 0.56
	Low	0.60 - 0.83	0.66 - 0.98	0.56 - 0.72
	Intermediate low	0.84 - 1.02	0.99 - 1.27	0.73 - 0.90
	Intermediate high	1.03 - 1.27	1.28 - 1.72	0.91 - 1.06
	High	1.28 - 1.75	1.73 - 2.40	1.07 - 1.32
	Very high	> 1.75	> 2.40	> 1.32
Accelerations (> 2 m·s^{-2})	Very low	< 0.56	< 0.60	< 0.56
	Low	0.56 - 0.83	0.60 - 1.00	0.56 - 0.72
	Intermediate low	0.84 - 1.05	1.01 - 1.37	0.73 - 0.90
	Intermediate high	1.06 - 1.35	1.38 - 1.89	0.91 - 1.09
	High	1.36 - 1.86	1.90 - 2.62	1.10 - 1.36
	Very high	> 1.86	> 2.62	> 1.36
Accelerations (> 3 m·s^{-2})	Very low	< 0.45	< 0.48	< 0.44
	Low	0.46 - 0.73	0.48 - 0.98	0.44 - 0.66
	Intermediate low	0.74 - 1.00	0.99 - 1.29	0.67 - 0.80
	Intermediate high	1.01 - 1.38	1.30 - 2.03	0.81 - 1.05
	High	1.39 - 2.14	2.04 - 3.14	1.06 - 1.51
	Very high	> 2.14	> 3.14	> 1.51
PlayerLoad™	Very low	< 0.59	< 0.73	< 0.53
	Low	0.59 - 0.87	0.73 - 1.00	0.54 - 0.75
	Intermediate low	0.88 - 1.07	1.01 - 1.36	0.76 - 0.92
	Intermediate high	1.08 - 1.35	1.37 - 1.68	0.93 - 1.13
	High	1.36 - 1.75	1.69 - 2.46	1.14 - 1.36
	Very high	> 1.75	> 2.46	> 1.36
Metres > 60% max (m)	Very low	< 0.42	< 0.15	< 0.51
	Low	0.42 - 0.72	0.15 - 0.85	0.51 - 0.66
	Intermediate low	0.73 - 1.00	0.86 - 1.35	0.67 - 0.91
	Intermediate high	1.01 - 1.32	1.36 - 1.81	0.92 - 1.09
	High	1.33 - 1.88	1.81 - 3.06	1.10 - 1.33
	Very high	> 1.88	> 3.06	> 1.33
Metres > 80% max (m)	Very low	0	0	< 0.19
	Low	0.01 - 0.35	0.01 - 0.09	0.19 - 0.41
	Intermediate low	0.36 - 0.72	0.11 - 0.93	0.42 - 0.65
	Intermediate high	0.73 - 1.18	0.94 - 2.02	0.66 - 1.00
	High	1.19 - 2.45	2.02 - 4.48	1.01 - 1.52
	Very high	> 2.45	> 4.48	> 1.52

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Positional Group Injuries

Front Row Forwards

Compared to the reference category, players with high (66.9 – 106.3m) weekly acceleration meters > 3 $m \cdot s^{-2}$ (OR = 0.15, 95% CIs = 0.04 – 0.61, $p < 0.01$) had a significantly lower injury risk (see Supplementary Table 12). When all chronic loads were combined, players with a low (0.46 – 0.74) HSR ACWR had a significantly lower odds of injury compared to the reference group (OR = 0.30, 95% CIs = 0.13 – 0.74, $p < 0.01$, see Supplementary Table 13).

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Supplementary Table 12: Injury risk (reported via odds ratios) associated with accumulated workloads and week-to-week change in workloads for Front Row Forwards.

	Classification	1 Weekly	2 Weekly	3 Weekly	4 Weekly	Weekly Change
TD (m)	Very low	/	/	/	/	/
	Low	0.61	0.88	2.12	0.59	1.53
	Intermediate low	0.73	1.43	2.00	1.01	0.98
	Intermediate high	0.76	0.89	1.49	0.85	1.56
	High	0.97	1.29	2.24	0.91	1.40
	Very high	0.87	2.08	1.58	0.41	1.49
HSR (m)	Very low	/	/	/	/	/
	Low	1.66	0.62	1.90	1.45	0.76
	Intermediate low	1.84	1.07	0.83	2.05	0.90
	Intermediate high	1.62	0.85	1.34	0.91	0.52
	High	1.79	0.57	1.93	1.37	0.75
	Very high	0.36	1.32	1.25	1.43	0.94
Accelerations (> 2 m·s^{-2})	Very low	/	/	/	/	/
	Low	0.76	1.57	1.25	1.46	0.89
	Intermediate low	0.50	2.99	0.88	1.35	0.35
	Intermediate high	1.11	2.75	0.75	1.11	0.80
	High	0.84	3.29	0.67	1.27	0.54
	Very high	0.65	4.09	1.20	0.44	0.93
Accelerations (> 3 m·s^{-2})	Very low	/	/	/	/	/
	Low	0.32	2.72	1.21	1.06	0.88
	Intermediate low	0.59	2.44	1.26	0.83	0.98
	Intermediate high	0.32	2.74	1.46	0.77	1.17
	High	**0.15***	3.72	0.72	1.29	0.86
	Very high	0.15	4.53	0.55	1.68	1.39
PlayerLoad™	Very low	/	/	/	/	/
	Low	0.87	1.19	0.80	0.58	0.71
	Intermediate low	0.46	2.90	1.40	0.56	1.40
	Intermediate high	0.50	2.52	0.87	0.60	0.74
	High	0.37	2.42	1.41	0.96	0.96
	Very high	0.57	1.76	1.41	0.29	1.22
Metres > 60% max (m)	Very low	/	/	/	/	/
	Low	0.77	0.78	1.97	0.45	0.67
	Intermediate low	1.06	0.60	0.79	1.23	0.99
	Intermediate high	1.34	0.98	1.24	1.68	0.76
	High	1.07	1.07	0.77	2.99	1.01
	Very high	0.42	0.42	0.68	4.57	0.95
Metres > 80% max (m)	Very low	/	/	/	/	/
	Low	0.29	2.82	1.09	0.75	0.28
	Intermediate low	0.24	1.71	2.30	0.46	0.35
	Intermediate high	0.65	2.54	1.62	0.78	0.38
	High	0.52	3.34	1.77	0.79	0.38
	Very high	0.49	2.43	0.80	1.08	0.31

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Accelerations (> 2 m·s^{-2}), acceleration meters > 2 m·s^{-2}; Accelerations (> 3 m·s^{-2}), acceleration meters > 3 m·s^{-2}; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity; * $p < 0.01$. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Supplementary Table 13: Injury risk associated with: (ACWR) acute: chronic workload ratios overall, (low chronic) acute: chronic workload ratios combined with low chronic workload and (high chronic) acute: chronic workload ratios combined with high chronic workloads for Front Row Forwards.

	Classification	Uncoupled ACWR	Low Chronic	High Chronic
TD (m)	Very low	/	/	/
	Low	0.70	0.64	0.58
	Intermediate low	0.90	0.62	0.66
	Intermediate high	0.76	0.70	0.67
	High	0.78	0.70	0.82
	Very high	0.43	0.64	1.07
HSR (m)	Very low	/	/	/
	Low	**0.30***	0.63	0.47
	Intermediate low	0.28	1.11	0.34
	Intermediate high	0.46	1.21	0.54
	High	0.65	0.65	0.29
	Very high	0.32	0.31	0.34
Accelerations (> 2 m·s^{-2})	Very low	/	/	/
	Low	0.50	0.97	0.34
	Intermediate low	0.73	0.88	0.60
	Intermediate high	0.33	0.48	0.74
	High	0.27	1.13	0.23
	Very high	0.51	0.61	0.48
Accelerations (> 3 m·s^{-2})	Very low	/	/	/
	Low	0.64	0.61	0.42
	Intermediate low	0.81	1.22	0.25
	Intermediate high	1.39	0.62	0.45
	High	1.19	0.71	0.41
	Very high	0.96	0.43	0.30
PlayerLoad™	Very low	/	/	/
	Low	0.67	1.30	0.39
	Intermediate low	1.68	0.36	0.56
	Intermediate high	1.39	0.91	0.55
	High	1.21	0.60	0.86
	Very high	0.77	0.48	0.77
Metres > 60% max (m)	Very low	/	/	/
	Low	0.49	0.36	0.66
	Intermediate low	0.28	0.27	0.36
	Intermediate high	0.60	0.55	0.63
	High	0.53	1.13	0.47
	Very high	0.86	0.18	0.62
Metres > 80% max (m)	Very low	/		/
	Low	1.67	/	0.84
	Intermediate low	2.21	0.81	1.26
	Intermediate high	1.56	0.75	1.00
	High	1.48	1.00	0.59
	Very high	0.87	0.48	0.91

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Accelerations (> 2 m·s^{-2}), acceleration meters > 2 m·s^{-2}; Accelerations (> 3 m·s^{-2}), acceleration meters > 3 m·s^{-2}; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity; * $p < 0.01$. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Second and Back Row Forwards

Players with an intermediate high workload for PlayerLoad™ ([1384 – 1704AU] OR = 4.88, 95% CIs = 1.61 – 14.78, $p < 0.01$), over 1-weekly periods were significantly more likely to be injured than the reference group. Similar findings were also reported for meters > 60% maximum velocity over 1-weekly periods (intermediate low workload [446 – 682m] OR = 4.18, 95% CIs = 1.47 – 11.88, $p < 0.01$; intermediate high workload [683 – 917m] OR = 7.69, 95% CIs = 2.50 – 23.67, $p < 0.001$, see Supplementary Table 14).

Players with a very high ACWR for TD (> 1.67) were shown to significantly reduce injury risk (OR = 0.23, 95% CIs = 0.08 – 0.61, $p < 0.01$). High chronic loads combined with a very high ACWR (> 1.38) for PlayerLoad™ significantly reduced injury risk (OR = 0.24, 95% CIs = 0.09 – 0.92, $p < 0.01$, see Supplementary Table 15).

Supplementary Table 14: Injury risk associated with accumulated workloads and week-to-week change in workloads for Second and Back Row Forwards.

	Classification	1 Weekly	2 Weekly	3 Weekly	4 Weekly	Weekly Change
TD (m)	Very low	/	/	/	/	/
	Low	1.98	0.83	1.13	1.74	1.12
	Intermediate low	1.70	0.77	1.14	1.49	1.18
	Intermediate high	2.22	0.91	1.77	1.21	1.59
	High	1.91	1.26	1.27	1.18	1.32
	Very high	2.42	1.42	0.90	1.85	1.41
HSR (m)	Very low	/	/	/	/	/
	Low	0.78	0.80	1.82	0.59	1.55
	Intermediate low	1.81	0.81	1.90	0.56	1.09
	Intermediate high	1.58	0.72	1.95	0.63	1.05
	High	1.50	0.81	1.69	0.69	1.66
	Very high	1.16	0.41	1.60	0.94	0.76
Accelerations (> 2 m·s^{-2})	Very low	/	/	/	/	/
	Low	1.86	0.48	2.03	0.88	1.01
	Intermediate low	1.55	0.41	2.26	0.77	0.66
	Intermediate high	2.35	0.38	2.79	0.82	1.00
	High	3.15	0.42	1.84	1.73	0.70
	Very high	1.97	0.53	1.54	1.51	0.94
Accelerations (> 3 m·s^{-2})	Very low	/	/	/	/	/
	Low	0.77	0.67	2.22	0.68	1.16
	Intermediate low	2.10	0.53	2.27	0.51	1.50
	Intermediate high	1.56	0.55	1.74	0.76	1.34
	High	0.97	0.36	2.06	1.13	1.30
	Very high	1.45	0.37	2.71	1.18	1.62
PlayerLoad™	Very low	/	/	/	/	/
	Low	2.86	0.55	1.38	1.32	1.09
	Intermediate low	2.63	0.36	2.68	1.52	1.71
	Intermediate high	**4.88***	0.60	1.98	1.08	1.34
	High	4.16	0.52	2.93	0.71	1.27
	Very high	6.17	0.38	1.95	1.22	0.90
Metres > 60% max (m)	Very low	/	/	/	/	/
	Low	1.94	0.73	0.46	1.58	1.46
	Intermediate low	**4.18***	1.18	0.66	1.24	0.87
	Intermediate high	**7.69***	1.18	0.65	1.41	1.75
	High	3.92	0.97	0.73	1.16	1.73
	Very high	3.73	1.47	0.42	1.26	0.73
Metres > 80% max (m)	Very low	/	/	/	/	/
	Low	1.20	0.77	1.70	0.57	1.31
	Intermediate low	0.95	1.40	1.13	0.63	1.73
	Intermediate high	1.13	0.74	1.77	0.54	1.26
	High	1.28	0.74	1.38	0.78	1.10
	Very high	0.48	1.87	0.93	0.63	1.59

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Accelerations (> 2 m·s^{-2}), acceleration meters > 2 m·s^{-2}; Accelerations (> 3 m·s^{-2}), acceleration meters > 3 m·s^{-2}; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity; * $p < 0.01$. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Supplementary Table 15: Injury risk associated with: (ACWR) acute: chronic workload ratios overall, (low chronic) acute: chronic workload ratios combined with low chronic workload and (high chronic) acute: chronic workload ratios combined with high chronic workloads for Second and Back Row Forwards.

	Classification	Uncoupled ACWR	Low Chronic	High Chronic
TD (m)	Very low	/	/	/
	Low	0.48	1.03	0.83
	Intermediate low	0.58	1.28	0.83
	Intermediate high	0.56	0.95	1.06
	High	0.47	1.12	0.97
	Very high	**0.23***	0.25	1.12
HSR (m)	Very low	/	/	/
	Low	1.10	0.15	2.69
	Intermediate low	0.89	1.14	1.34
	Intermediate high	0.96	1.00	2.47
	High	0.95	0.89	1.27
	Very high	0.95	0.90	1.48
Accelerations (> 2 m·s^{-2})	Very low	/	/	/
	Low	0.37	0.60	0.71
	Intermediate low	**0.27***	1.14	0.70
	Intermediate high	0.39	1.31	0.49
	High	0.35	1.24	0.92
	Very high	0.34	0.48	0.78
Accelerations (> 3 m·s^{-2})	Very low	/	/	/
	Low	1.11	0.64	1.24
	Intermediate low	0.48	1.13	0.68
	Intermediate high	1.03	1.10	0.62
	High	0.90	1.11	0.79
	Very high	0.56	0.42	1.33
PlayerLoad™	Very low	/	/	/
	Low	0.26	1.69	0.32
	Intermediate low	0.35	1.93	0.63
	Intermediate high	0.37	1.14	0.89
	High	**0.10***	1.73	0.64
	Very high	**0.15***	0.64	**0.24***
Metres > 60% max (m)	Very low	/	/	/
	Low	0.53	0.75	1.67
	Intermediate low	**0.26***	1.33	1.25
	Intermediate high	**0.27***	1.58	0.97
	High	0.35	2.95	1.31
	Very high	0.36	1.05	0.71
Metres > 80% max (m)	Very low	/		/
	Low	1.20	/	2.34
	Intermediate low	1.40	2.57	1.28
	Intermediate high	1.26	1.43	2.04
	High	1.25	1.00	1.82
	Very high	1.46	1.73	1.14

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Accelerations (> 2 m·s^{-2}), acceleration meters > 2 m·s^{-2}; Accelerations (> 3 m·s^{-2}), acceleration meters > 3 m·s^{-2}; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity; * $p < 0.01$. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Halfbacks

Cumulative Loads and Weekly Change

Weekly loads for acceleration meters > 2 $m \cdot s^{-2}$ significantly increased injury risk for intermediate low (582 – 711m) workloads (OR = 7.01, 95% CIs = 1.65 – 29.80, $p < 0.01$, see Supplementary Table 16). Over 2-week cumulative periods, a high TD (36,276 – 42,486m) significantly reduced injury risk (OR = 0.13, 95% CIs = 0.03 – 0.56, $p < 0.01$). An Intermediate low (2566 – 2985AU) and high (3429 – 4249AU) 2-week cumulative PlayerLoad™ significantly reduced injury risk (OR = 0.14, 95% CIs = 0.03 – 0.63, $p = 0.01$; OR = 0.03, 95% CIs = 0.004 – 0.26, $p < 0.01$, respectively). Intermediate low meters > 60% maximum velocity (1473 – 1876m) over 2-week periods also reduced injury risk compared to the reference category (OR = 0.07, 95% CIs = 0.01 – 0.39, $p < 0.01$). Over 3-week cumulative periods, a low PlayerLoad™ (3186 – 3861AU) workload significantly increased injury risk (OR = 7.78, 95% CIs = 2.19 – 27.7, $p < 0.01$). Greater weekly changes appeared to reduce injury risk compared to the reference category. This was reported for acceleration meters > 2 $m \cdot s^{-2}$ (OR < 1, $p < 0.01$).

The Acute: Chronic Workload Ratio and Chronic Loading

When all chronic workloads were combined, an intermediate high ACWR for acceleration meters > 3 $m \cdot s^{-2}$ (1.01 – 1.29) significantly reduced injury risk (OR = 0.08, 95% CIs = 0.02 – 0.39, $p < 0.01$, see Supplementary Table 17).

Supplementary Table 16: Injury risk associated with accumulated workloads and week-to-week change in workloads for Halfbacks.

	Classification	1 Weekly	2 Weekly	3 Weekly	4 Weekly	Weekly Change
TD (m)	Very low	/	/	/	/	/
	Low	0.92	0.41	2.80	1.19	0.48
	Intermediate low	1.53	0.35	3.05	1.86	0.64
	Intermediate high	2.78	0.18	2.71	1.62	0.86
	High	1.44	**0.13***	2.65	3.40	0.51
	Very high	1.02	0.40	1.72	2.48	0.57
HSR (m)	Very low	/	/	/	/	/
	Low	3.79	0.76	1.14	0.83	0.90
	Intermediate low	3.76	0.54	4.72	0.39	0.83
	Intermediate high	9.38	0.11	2.39	0.24	0.58
	High	8.78	0.32	3.79	0.41	0.51
	Very high	5.68	0.41	2.10	0.51	0.39
Accelerations (> 2 m·s^{-2})	Very low	/	/	/	/	/
	Low	1.59	0.65	0.56	1.18	0.73
	Intermediate low	**7.01***	0.49	1.33	0.33	0.47
	Intermediate high	0.93	0.33	2.16	0.41	**0.23***
	High	10.30	0.19	2.52	0.19	**0.22***
	Very high	10.70	0.19	5.36	0.23	**0.18***
Accelerations (> 3 m·s^{-2})	Very low	/	/	/	/	/
	Low	1.77	1.10	0.43	1.66	0.37
	Intermediate low	3.04	1.46	0.72	0.99	0.56
	Intermediate high	5.80	1.92	0.64	0.45	0.47
	High	7.57	0.69	2.52	0.07	0.34
	Very high	14.66	1.47	2.01	0.12	0.22
PlayerLoad™	Very low	/	/	/	/	/
	Low	0.75	0.42	**7.78***	0.56	0.45
	Intermediate low	4.74	0.14	3.40	0.14	0.50
	Intermediate high	3.48	0.16	2.31	0.57	0.39
	High	2.62	**0.03***	9.12	0.78	0.22
	Very high	1.81	0.22	9.79	0.56	0.25
Metres > 60% max (m)	Very low	/	/	/	/	/
	Low	4.43	0.24	2.17	0.49	0.73
	Intermediate low	7.53	**0.07***	1.05	2.05	0.82
	Intermediate high	7.55	0.34	1.12	1.22	0.56
	High	5.00	0.29	0.95	1.56	0.36
	Very high	6.24	0.45	0.96	1.33	0.56
Metres > 80% max (m)	Very low	/	/	/	/	/
	Low	0.36	1.14	0.42	0.62	1.96
	Intermediate low	0.21	2.99	0.19	0.86	5.68
	Intermediate high	1.87	5.26	0.09	1.49	4.06
	High	1.15	5.99	0.06	0.81	1.82
	Very high	1.92	9.16	0.04	0.67	3.57

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Accelerations (> 2 m·s^{-2}), acceleration meters > 2 m·s^{-2}; Accelerations (> 3 m·s^{-2}), acceleration meters > 3 m·s^{-2}; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity; * $p < 0.01$. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Supplementary Table 17: Injury risk associated with: (ACWR) acute: chronic workload ratios overall, (low chronic) acute: chronic workload ratios combined with low chronic workload and (high chronic) acute: chronic workload ratios combined with high chronic workloads for Halfbacks.

	Classification	Uncoupled ACWR	Low Chronic	High Chronic
TD (m)	Very low	/	/	/
	Low	0.90	0.58	1.62
	Intermediate low	0.74	2.32	0.78
	Intermediate high	1.48	2.65	0.83
	High	2.07	1.19	1.52
	Very high	1.86	1.42	2.11
HSR (m)	Very low	/	/	/
	Low	0.43	0.98	2.35
	Intermediate low	0.56	1.28	1.47
	Intermediate high	0.45	1.25	4.49
	High	0.44	0.72	3.07
	Very high	0.42	1.28	3.83
Accelerations (> 2 m·s^{-2})	Very low	/	/	/
	Low	0.57	0.96	6.41
	Intermediate low	0.40		4.18
	Intermediate high	0.23	0.96	2.00
	High	0.65	2.03	6.41
	Very high	0.35	0.64	5.47
Accelerations (> 3 m·s^{-2})	Very low	/	/	/
	Low	0.47	1.22	1.59
	Intermediate low	0.28	0.00	0.98
	Intermediate high	**0.08***	1.33	2.10
	High	0.22	1.14	0.64
	Very high	0.24	0.95	0.96
PlayerLoad™	Very low	/	/	/
	Low	0.70	0.96	5.46
	Intermediate low	1.02	1.17	7.64
	Intermediate high	0.82	1.38	5.46
	High	1.11	1.47	6.70
	Very high	1.05	1.25	4.17
Metres > 60% max (m)	Very low	/	/	/
	Low	0.50	1.25	1.36
	Intermediate low	0.70	1.02	1.31
	Intermediate high	0.78	0.96	2.98
	High	0.63	1.61	2.98
	Very high	0.45	0.72	1.36
Metres > 80% max (m)	Very low	/	/	/
	Low	1.49	0.67	5.00
	Intermediate low	2.01	0.44	10.32
	Intermediate high	0.71	0.28	11.46
	High	0.41	0.91	6.41
	Very high	0.20	0.28	0.96

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Accelerations (> 2 m·s^{-2}), acceleration meters > 2 m·s^{-2}; Accelerations (> 3 m·s^{-2}), acceleration meters > 3 m·s^{-2}; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity; * $p < 0.01$. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Centres

Cumulative Loads and Weekly Change

Low (828 - 1257m), acceleration meters > 2 m·s^{-2} significantly increased injury risk over 2-week periods (6.81, 95% CIs = 1.71 – 27.09, p < 0.01, see Supplementary Table 18). Intermediate low (154 – 195m) acceleration meters > 3 m·s^{-2} significantly increased injury risk over 2-week cumulative periods (OR = 8.90, 95% CIs = 1.78 – 44.50, p < 0.01).

The Acute: Chronic Workload Ratio and Chronic Loading

High chronic loading for TD, combined with high (1.12 – 1.31) and very high (> 1.31) ACWRs significantly increased the risk of injury compared to the reference group (high workload OR = 4.14, 95% CIs = 1.47 – 11.66, p < 0.01; very high workload OR = 4.06, 95% CIs = 1.43 – 11.52, p < 0.01, see Supplementary Table 19).

Supplementary Table 18: Injury risk associated with accumulated workloads and week-to-week change in workloads for Centres.

	Classification	1 Weekly	2 Weekly	3 Weekly	4 Weekly	Weekly Change
TD (m)	Very low	/	/	/	/	/
	Low	0.83	2.66	0.54	2.25	1.51
	Intermediate low	0.61	3.29	0.51	2.52	0.96
	Intermediate high	1.07	5.45	0.46	2.19	1.71
	High	0.55	5.81	0.34	3.88	1.87
	Very high	0.42	6.62	0.33	6.54	1.83
HSR (m)	Very low	/	/	/	/	/
	Low	0.37	1.15	0.71	0.58	1.75
	Intermediate low	0.38	2.93	1.00	1.52	1.58
	Intermediate high	0.27	5.55	0.90	1.68	1.29
	High	0.27	4.21	0.29	3.43	1.10
	Very high	0.26	3.38	0.36	6.54	0.39
Accelerations ($> 2\ m \cdot s^{-2}$)	Very low	/	/	/	/	/
	Low	0.45	**6.81***	0.35	3.13	1.33
	Intermediate low	0.75	3.99	0.21	0.46	1.83
	Intermediate high	0.88	7.57	0.33	2.86	1.34
	High	0.52	11.00	0.16	3.48	1.59
	Very high	0.76	14.29	0.18	2.18	0.87
Accelerations ($> 3\ m \cdot s^{-2}$)	Very low	/	/	/	/	/
	Low	0.92	2.38	0.83	3.71	0.76
	Intermediate low	1.90	**8.90***	0.42	1.48	0.66
	Intermediate high	1.20	3.19	0.63	1.32	0.66
	High	0.92	7.27	0.38	2.97	0.84
	Very high	0.85	10.57	0.32	3.35	0.59
PlayerLoad™	Very low	/	/	/	/	/
	Low	1.48	1.59	0.71	1.71	1.42
	Intermediate low	0.83	1.33	0.74	1.05	1.51
	Intermediate high	0.30	2.98	0.88	0.76	1.57
	High	1.90	3.05	0.37	1.06	0.85
	Very high	0.54	4.63	0.40	2.03	1.58
Metres > 60% max (m)	Very low	/	/	/	/	/
	Low	3.74	0.47	1.93	1.39	2.96
	Intermediate low	4.17	1.03	0.43	1.37	2.28
	Intermediate high	4.79	1.16	0.31	3.13	1.93
	High	4.43	1.35	0.25	4.38	1.91
	Very high	4.96	1.02	0.46	3.26	0.88
Metres > 80% max (m)	Very low	/	/	/	/	/
	Low	0.73	0.42	3.21	0.37	1.01
	Intermediate low	0.49	0.20	3.33	0.93	1.44
	Intermediate high	1.48	0.41	2.40	0.52	0.86
	High	1.36	0.65	2.92	0.47	0.92
	Very high	1.46	0.61	1.69	0.36	1.58

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Accelerations ($> 2\ m \cdot s^{-2}$), acceleration meters $> 2\ m \cdot s^{-2}$; Accelerations ($> 3\ m \cdot s^{-2}$), acceleration meters $> 3\ m \cdot s^{-2}$; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity; * $p < 0.01$. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Supplementary Table 19: Injury risk associated with: (ACWR) acute: chronic workload ratios overall, (low chronic) acute: chronic workload ratios combined with low chronic workload and (high chronic) acute: chronic workload ratios combined with high chronic workloads for Centres.

	Classification	Uncoupled ACWR	Low Chronic	High Chronic
TD (m)	Very low	/	/	/
	Low	0.37	0.58	1.93
	Intermediate low	1.56	2.33	2.07
	Intermediate high	2.52	1.40	2.14
	High	2.17	2.63	4.14*
	Very high	1.87	1.00	4.06*
HSR (m)	Very low	/	/	/
	Low	1.34	0.15	0.72
	Intermediate low	0.75	0.65	2.88
	Intermediate high	0.98	1.22	0.73
	High	2.49	2.32	1.43
	Very high	4.86	0.48	1.64
Accelerations (> 2 m·s^{-2})	Very low	/	/	/
	Low	0.92	1.36	0.65
	Intermediate low	0.64	1.36	2.26
	Intermediate high	0.84	1.36	0.62
	High	0.82	2.44	1.25
	Very high	0.94	3.07	1.84
Accelerations (> 3 m·s^{-2})	Very low	/	/	/
	Low	0.99	0.98	2.69
	Intermediate low	0.52	1.31	0.98
	Intermediate high	0.50	1.25	0.96
	High	0.61	2.56	0.80
	Very high	1.48	1.58	1.92
PlayerLoad™	Very low	/	/	/
	Low	2.30	0.65	3.59
	Intermediate low	0.80	1.75	1.82
	Intermediate high	1.37	2.21	1.00
	High	1.97	3.78	2.51
	Very high	1.60	1.80	1.60
Metres > 60% max (m)	Very low	/	/	/
	Low	0.55	0.44	1.23
	Intermediate low	0.16	3.05	1.67
	Intermediate high	0.63	1.89	0.56
	High	0.57	1.62	1.71
	Very high	0.69	1.58	1.92
Metres > 80% max (m)	Very low	/	/	/
	Low	4.85	2.60	0.50
	Intermediate low	5.40	1.14	0.96
	Intermediate high	2.84	1.86	0.61
	High	3.22	2.95	0.83
	Very high	2.30	2.87	0.87

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Accelerations (> 2 m·s^{-2}), acceleration meters > 2 m·s^{-2}; Accelerations (> 3 m·s^{-2}), acceleration meters > 3 m·s^{-2}; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity; * $p < 0.01$. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

The Back 3

Cumulative Loads and Weekly Change

Injury risk was not significantly related to any workload variable for any workload group across all workload calculations (see Supplementary Table 20).

The Acute: Chronic Workload Ratio and Chronic Loading

Players who were in a low chronic loading state for meters > 60% maximum velocity, combined with an intermediate high ACWR (1.36 – 1.81) were significantly more likely to be injured (OR = 7.8, 95% CIs = 1.65 – 37.23, p = 0.01, see Supplementary Table 21).

Supplementary Table 20: Injury risk associated with accumulated workloads and week-to-week change in workloads for the Back 3.

	Classification	1 Weekly	2 Weekly	3 Weekly	4 Weekly	Weekly Change
TD (m)	Very low	/	/	/	/	/
	Low	1.09	0.53	2.44	0.98	0.88
	Intermediate low	1.08	0.83	2.79	0.59	0.96
	Intermediate high	0.64	1.02	2.68	1.10	1.16
	High	0.72	1.67	2.20	0.53	1.56
	Very high	0.77	2.90	1.63	1.12	2.02
HSR (m)	Very low	/	/	/	/	/
	Low	0.96	1.25	1.74	1.15	1.41
	Intermediate low	1.08	1.96	1.70	1.03	0.83
	Intermediate high	0.61	1.58	1.38	1.14	0.71
	High	0.97	1.17	2.23	1.10	0.80
	Very high	0.77	1.46	1.49	1.87	0.92
Accelerations (> 2 m·s^{-2})	Very low	/	/	/	/	/
	Low	1.41	1.13	0.95	2.41	0.70
	Intermediate low	1.25	0.75	0.68	3.47	0.43
	Intermediate high	0.89	1.71	0.75	0.76	0.85
	High	0.69	1.39	1.04	2.98	0.73
	Very high	1.05	1.24	1.21	1.53	0.80
Accelerations (> 3 m·s^{-2})	Very low	/	/	/	/	/
	Low	2.25	1.13	0.93	1.07	1.47
	Intermediate low	2.35	1.06	0.72	1.18	1.32
	Intermediate high	1.56	2.08	0.78	1.45	1.68
	High	2.16	1.13	0.45	1.05	1.13
	Very high	1.23	1.66	0.33	3.22	1.43
PlayerLoad™	Very low	/	/	/	/	/
	Low	1.17	0.50	1.29	1.19	0.93
	Intermediate low	1.49	0.37	1.92	2.03	0.92
	Intermediate high	1.76	0.34	1.93	2.30	0.70
	High	1.80	0.66	2.63	0.50	1.08
	Very high	2.85	0.39	1.45	1.84	1.17
Metres > 60% max (m)	Very low	/	/	/	/	/
	Low	0.38	0.89	1.05	1.81	2.12
	Intermediate low	0.37	1.06	1.97	1.73	1.58
	Intermediate high	0.58	1.81	1.65	0.55	1.24
	High	0.26	2.41	2.11	1.70	1.55
	Very high	0.21	1.25	0.74	3.98	1.25
Metres > 80% max (m)	Very low	/	/	/	/	/
	Low	1.77	0.63	5.38	0.43	0.54
	Intermediate low	1.87	1.03	8.11	0.73	1.22
	Intermediate high	3.29	0.85	7.40	0.50	0.64
	High	1.75	2.00	4.19	0.54	0.93
	Very high	1.65	2.00	5.70	0.58	0.89

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Accelerations (> 2 m·s^{-2}), acceleration meters > 2 m·s^{-2}; Accelerations (> 3 m·s^{-2}), acceleration meters > 3 m·s^{-2}; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity; * p < 0.01. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).

Supplementary Table 21: Injury risk associated with: (ACWR) acute: chronic workload ratios overall, (low chronic) acute: chronic workload ratios combined with low chronic workload and (high chronic) acute: chronic workload ratios combined with high chronic workloads for the Back 3.

	Classification	Uncoupled ACWR	Low Chronic	High Chronic
TD (m)	Very low	/	/	/
	Low	1.06	1.32	0.76
	Intermediate low	1.26	0.47	1.36
	Intermediate high	0.89	0.65	0.63
	High	0.78	3.07	1.10
	Very high	1.70	2.50	1.23
HSR (m)	Very low	/	/	/
	Low	0.65	0.36	1.46
	Intermediate low	0.54	1.17	2.13
	Intermediate high	0.84	0.38	1.25
	High	1.13	2.41	0.78
	Very high	1.89	1.64	2.57
Accelerations (> 2 m·s^{-2})	Very low	/	/	/
	Low	0.74	2.19	0.50
	Intermediate low	1.77	1.63	0.81
	Intermediate high	0.53	3.37	1.28
	High	1.94	2.09	0.48
	Very high	1.59	2.50	1.17
Accelerations (> 3 m·s^{-2})	Very low	/	/	/
	Low	0.45	1.39	0.33
	Intermediate low	0.75	2.85	0.84
	Intermediate high	1.08	2.61	0.69
	High	1.05	2.14	0.96
	Very high	1.33	3.44	0.98
PlayerLoad™	Very low	/	/	/
	Low	0.63	0.52	1.37
	Intermediate low	0.99	0.38	2.04
	Intermediate high	0.41	1.89	1.40
	High	0.59	1.64	1.46
	Very high	0.91	1.93	0.96
Metres > 60% max (m)	Very low	/	/	/
	Low	1.65	0.98	0.88
	Intermediate low	1.13	2.09	0.61
	Intermediate high	2.53	7.83	1.00
	High	2.37	3.83	1.13
	Very high	5.38	4.59	0.63
Metres > 80% max (m)	Very low	/		/
	Low	0.37	/	0.80
	Intermediate low	0.71	1.03	1.33
	Intermediate high	0.24	1.69	0.19
	High	0.45	1.69	0.92
	Very high	0.44	2.37	0.60

NOTE: TD, total distance in meters; HSR, high-speed running distance in meters; Accelerations (> 2 m·s^{-2}), acceleration meters > 2 m·s^{-2}; Accelerations (> 3 m·s^{-2}), acceleration meters > 3 m·s^{-2}; Meters > 60% max, meters covered above 60% of maximum velocity; Meters > 80% max, meters covered above 80% of maximum velocity; * $p < 0.01$. Total distance (orange fill) is over 2 seasons (2017/18 & 2018/19). All other loading variables are over 1 season (2018/19 season).