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Relationship between GPS workload and injury risk in elite rugby league players

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Relationship between GPS workload and injury risk in elite rugby league players

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CHAPTER ONE: PRELIMINARY MATERIAL

1.1 EXECUTIVE SUMMARY

A systematically planned and distributed training program is required for elite athletes to have positive adaptations to training workloads, with minimal risk of injury. *Workload-injury* investigations in team sports typically quantify workload in absolute terms, for example the workload performed in a week versus injury. However, *workload-performance* investigations have examined absolute workload performed in one week (referred to as acute workload) relative to four-week chronic workload (i.e. four-week average acute workload). The logic behind this comparison of workloads is the provision of a workload index, which provides an indication of whether the athlete's recent acute workload is greater, less than or equal to the workload that the athlete has been prepared for during the preceding chronic period. This method is referred to as the *acute:chronic workload ratio*. The purpose of this thesis was to investigate whether acute workload and chronic workload could be mapped and modelled to predict injury in elite rugby league players.

In study one, data were collected from 53 players via global positioning systems (GPS) during two elite rugby league seasons. The acute:chronic workload ratio was calculated by dividing acute workload (one-week total distance) by chronic workload (four-week average acute workload). A value of greater than 1 represented an acute workload greater than chronic workload. All workload data were classified into very-low through very-high ranges by z-scores. Compared with all other ratios, a very-high acute:chronic workload ratio (≥2.11) demonstrated the greatest risk of injury in the current week (16.7% injury risk) and subsequent week (11.8% injury risk). Players with a high chronic workload (>16,095 m) combined with a very-high two-week average acute:chronic workload ratio (≥1.54) had the greatest risk of injury (28.6% injury risk). Additionally, having a high chronic workload combined with a moderate workload ratio (1.02-1.18) had a smaller risk of injury than low chronic workload combined with several workload ratios (relative risk [RR] range from 0.3-0.7 ×/÷ 1.4-4.4; likelihood range = 88-94%, likely). Considering acute and chronic workloads in isolation (i.e., not as ratios) did not consistently predict injury risk.

These findings demonstrate that acute:chronic workload ratios are a greater predictor of injury than either acute or chronic workload in isolation. Additionally, compared with players that have a low chronic workload, players with a high chronic workload are *more resistant to injury*

with moderate-low through moderate-high (0.85-1.35) acute:chronic workload ratios and *less resistant to injury* when subjected to large increases in acute workload, which result in very-high acute:chronic workload ratios ~1.5.

Study two of this thesis investigated the combined influence of between-match recovery time and workload on injury risk. Between-match workloads were calculated during <7 day, and ≥7 day between-match recovery times. Injury risk was greater with <7 days than ≥7 days between matches (RR = 1.5 ×/÷ 1.5; likelihood = 91.1%, likely). During <7 day between-match recovery times: (1) high chronic workloads were associated with a smaller risk of injury than lower chronic workloads (RR range from 0.4-0.5 ×/÷ 1.2-3.1; likelihood range = 89-99%, likely-very likely) and (2) a very-high acute:chronic workload ratio (≥1.69) was associated with greater injury risk than all other acute:chronic workload ratios (RR range from 2.7-5.3 ×/÷ 1.2-2.7; likelihood range = 94-99%, likely-almost certainly). High, and very-high between-match workloads were not associated with a greater risk of injury than low, and very-low between-match workloads (RR range from 0.4-1.3 ×/÷ 1.0-41.5; likelihood range = 2-55%, very unlikely-possibly).

The findings from study two demonstrate that although injury risk is greater with <7 days than ≥7 days recovery between matches, workloads can be manipulated to decrease the injury risk associated with shorter recovery time between matches. Furthermore, provided that very-high acute:chronic workload ratios are not prescribed, higher between-match workloads can be achieved without increasing injury risk in elite rugby league players.

The work within this thesis is the first to investigate injury risk in relation to acute and chronic workloads derived from GPS in elite rugby league players. We have provided threshold values for modelling acute and chronic workloads to predict the relative risk and likelihood of sustaining an injury. Practitioners should note that higher chronic workloads and the systematic increase of acute workloads in relation to chronic workloads can decrease injury risk in elite rugby league players.

1.2 THESIS CERTIFICATION

I, William Hulin, declare that this thesis is entirely my own work, unless otherwise referenced or acknowledged. The studies presented within chapters three and four have been improved subsequent to being anonymously peer-reviewed through a scientific journal. The work within this thesis is submitted as a requirement for the award of the degree Master of Philosophy, in the School of Medicine, University of Wollongong. This document has not been submitted for assessment at any other academic institution.

William Hulin

25th September, 2015

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1.6 LIST OF ABBREVIATIONS

1-RM	One repetition maximum
AU	Arbitrary units
CI	Confidence interval
CV	Coefficient of variation
GPS	Global positioning system
HSR	Distance covered at high-speed running >4.17 $m \cdot sec^{-1}$
Hz	Hertz
ICC	Intraclass correlation coefficient
RPE	Rating of perceived exertion
RR	Relative risk
SEE	Standard error of estimate
SPSS	Statistical package for social sciences
s-RPE	Session-rating of perceived exertion x session duration
TD	Total distance covered
TE	Typical error
TRIMP	Training impulse
VHSR	Distance covered at very high-speed running > 5.56 $m \cdot sec^{-1}$
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2max}$	Maximal oxygen uptake
r	Correlation

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The St. George Illawarra Dragons Rugby League Football Club partially provided the scholarship funds that allowed me to complete this work, I will always be very grateful for that. Also, there are a number of staff members from the club that I wish to thank; Andrew Gray who organised and facilitated the data collection for this thesis and provided me with a wonderful opportunity to work in elite rugby league; Dan Lawson, for methodically and consistently collecting the injury data used to complete this work; Nathan Pickworth and John Davey for assistance with GPS data collection. I would also like to thank the players that participated in these studies. It has been a great pleasure to be able to work with these athletes throughout this thesis. I hope the findings from this work can be used to allow them to continue doing what they do with great success.

To my Mum, Dad, and sister, I cannot thank you enough for the support that you have given me. You have always been there for me and encouraged me to do what I want to do, even when others have advised against it. Finally, my girlfriend Lauren, who left her family, friends and job, to move interstate and support me through this degree, I could not have done this without you and I will always be grateful.

1.8 PUBLICATIONS

Original investigations

Study one – chapter three

Hulin, B., Gabbett, T., Lawson, D., Caputi, P., & Sampson, J. (2015). The acute:chronic workload ratio predicts injury: high chronic workload may decrease injury risk in elite rugby league players. *British Journal of Sports Medicine*. In press.

Study two – chapter four

Hulin, B., Gabbett, T., Caputi, P., & Sampson, J. (2015). Combined influence of between-match recovery time and workload on injury risk in elite rugby league players. *British Journal of Sports Medicine*. Submitted for publication.

Conference presentation

Hulin, B., Gabbett, T., Caputi, P., Lawson, D., & Sampson, J. (2015). Very-high chronic workload is not associated with injury in elite rugby league players. *World Congress on Science and Football; Copenhagen, Denmark*.

1.9 STATEMENT OF AUTHOR CONTRIBUTION

Billy Hulin

Billy is responsible for the majority of the work presented in this thesis. He completed the literature review, experimental design, workload data collection, data processing and analysis, statistical analysis and the written work within this thesis.

Tim Gabbett

Tim provided intellectual contribution to help design the projects inside this thesis. Tim also critically reviewed this thesis and the written work that is either accepted for publication or submitted for peer-review.

Daniel Lawson

A qualified physiotherapist working in professional rugby league, Daniel collected the injury data that was used to conduct the studies within this thesis. He also provided guidance interpreting injury data during the data analysis phase.

Peter Caputi

Peter is an Associate Professor and Head of the School of Psychology at University of Wollongong. He provided intellectual aid for the statistical methods used in these projects and critical review of all written material.

John Sampson

As the principal supervisor of this thesis, John contributed to the concept and design of the research questions and facilitated ethical approval and informed consent from participants. John has also critically reviewed this thesis and the written work within, which is either accepted for publication or submitted for peer-review.

CHAPTER TWO: LITERATURE REVIEW

2.1 GENERAL INTRODUCTION

The competitive performance of elite athletes is dependent upon the development and prescription of systematic training programs. The ultimate goal of these programs is to optimise athletic performance, without increasing the likelihood of injury. As such, training programs for individual, and team sports are typically planned, distributed and varied in a periodic or cyclic fashion, known as periodisation (Stone, *et al.*, 1999a; Stone, *et al.*, 1999b). Training programs can be varied through the manipulation of either the amount of work performed (i.e. volume) or the effort required to complete the prescribed work (i.e. intensity; Issurin, 2010; Plisk, 2008; Plisk & Stone, 2003; Stone, *et al.*, 1999a; Stone, *et al.*, 1999b). The effect of training promotes physiological adaptations to an organism, which have been described by Selye's theory of general adaptation (Selye, 1959; Selye, 1974). In this model, the initial response to a stressor is negative, termed, the alarm stage. The 'alarm stage' is characterised by the physiological state and performance of the organism decreasing following the stressor's initial application, for example heart rate and respiratory rate increase (Selye, 1959; Selye, 1974). This negative response is followed by positive adaptations such as increased maximal oxygen uptake ($\dot{V}O_{2max}$; Billat *et al.*, 2003; Seiler, & Tønnessen, 2009), intensity at which pulmonary ventilation increases disproportionately with oxygen consumption (ventilatory threshold; Tjelta, Tjelta, & Dystrand, 2012), and number and density of skeletal muscle mitochondria (Daussin *et al.*, 2007; Hood, 2009). These responses are recognised as training adaptations and can occur in as little as three days (i.e. increases in plasma volume; Green, Jones, & Painter, 1990), whilst others can require six weeks of training (i.e. increases in ventilatory threshold; Chin *et al.*, 2001). These adaptations to the stressor, referred to as supercompensation, improve the performance of the organism.

Selye's model also proposes that when the magnitude of the stress is either too large, enforced for too long, or additional stressors (e.g. travel, occupational stress, poor quality of sleep) are imposed on the organism, then exhaustion occurs, resulting in a loss of positive adaptations and a decrease in performance (Selye, 1959; Selye, 1974). Practitioners in team sport believe that during these periods, when fatigue is high and fitness is low, an increased risk of the athlete sustaining an injury is present (McCall *et al.*, 2014). Collectively, Seyle's model, along with the above-mentioned studies (Issurin, 2010; McCall *et al.*, 2014; Plisk, 2008; Plisk & Stone, 2003), highlight that elite athletes require a training program that is systematically planned and distributed so that positive adaptations will occur, whilst minimising the risk of negative outcomes such as injury. It is therefore essential that an athlete's workload is prescribed and quantified in a fashion that facilitates these positive outcomes, while decreasing the likelihood of injury.

2.2 METHODS OF REPORTING INJURIES IN TEAM SPORT

Comparing the incidence of injury in team sport is typically done by calculating the number of injuries sustained per 1000 hours of training and/or match-play (King, *et al.*, 2009). This method allows for a variety of sports to be compared equally, as the differing durations of each sport may potentially result in an over- or under-estimation of comparative injury incidence. Injury rates of 58 and 211 per 1000 hours of rugby league match-play have been reported (Walker, 1985; Estell *et al.*, 1995), which are higher than the training injury rates demonstrated by others (20.7/1000 hours; Gabbett & Godbolt, 2010).

Relating the findings from multiple injury investigations in team sport can be difficult due to the use of inconsistent definitions of injury (King, *et al.*, 2010). Some examples of injury definitions used throughout the literature are: (1) any pain or disability suffered by a player during a match or training session and subsequently assessed during or immediately after the match or training session (Gabbett, 2004a), (2) any pain or disability suffered by a player during a training session that prevented the player from completing that session (Gabbett & Domrow, 2005), (3) any injury that resulted in a loss of either match-time or greater than one training session (Hulin *et al.*, 2014), and (4) any injury that resulted in a player missing a match (Gibbs, 1993; Murray, Gabbett, & Chamari, 2015). Although these definitions of injury differ, one consistent outcome is that they are all binary, i.e. only two possible outcomes can occur – injury or no injury.

Expert opinion has been provided on injury definitions in a variety of team sports (Fuller *et al.*, 2006; Fuller *et al.*, 2007; Hodgson, *et al.*, 2007; King, *et al.*, 2009; Orchard & Hoskins, 2007). In rugby league, King *et al.*, (2009) recommended that injuries be defined as: *"Any pain or disability that occurs during participation in rugby league match or training activities"*. Injuries can be further classified as either: (1) a 'medical attention injury' – an injury that results in a player requiring first aid or medical attention, e.g. a player receiving medical treatment following training, however the player can continue to participate in subsequent training sessions or (2) any injury that results in a player being unable to partake in training and/or match activities, referred to as a 'time loss' injury (King, *et al.*, 2009). Additionally, medical attention injuries may be viewed as subjective; an injury that may require treatment for one player may be considered irrelevant and not requiring treatment by another player. The influence of time loss injury on performance in team sport athletes is obvious and simple; a player sustaining such an injury cannot participate in training and/or match-play, therefore performance is not possible. As such, time loss injuries can be considered as a measurable factor that can affect the capability of athletic performance.

Quantifying the absolute risk of sustaining an injury involves comparing of the number of injury occurrences relative to the number of exposures to an injury risk factor (Bahr & Holme, 2003; Hulin *et al.*, 2014). For example, 10 injuries sustained by 86 athletes over a particular time period, would provide an absolute injury risk of 11.6% (10/86 = 0.116). This method allows for a comparison of the relative risk (RR) of injury between two groups by dividing one groups absolute injury risk by another groups absolute injury risk (Bahr & Holme, 2003). When considering workload as an injury risk factor, Hulin *et al.* (2014) demonstrated that elite cricket fast bowlers with a chronic (i.e. four-week rolling average) bowling workload of 150-180 deliveries had an injury risk of approximately 1.3%, whereas fast bowlers with a chronic bowling workload of less than 30 deliveries had an injury risk of approximately 9.0%. Therefore, the RR of injury for fast bowlers with chronic workloads of less than 30 deliveries, when compared with chronic workloads between 150-180 deliveries, would be 6.9 (RR = 9.0/1.3 = 6.9). This example is just one of many studies that have demonstrated relationships between workload and injury in elite team sport athletes (Hulin *et al.*, 2014; Gabbett, 2010; Rogalski, *et al.*, 2013).

2.3 METHODS OF QUANTIFYING WORKLOAD AND ASSOCIATIONS WITH INJURY IN TEAM SPORT

2.3.1 Quantifying workload

Workload, also known as training load or "load", has been referred to as the dose of training completed by an athlete and can be quantified using either external measures of training (i.e. the training completed by an athlete [e.g. distance covered, weight lifted, power output]) or internal measures of training (i.e. an athlete's response to an external workload [e.g. heart rate, oxygen uptake {$\dot{V}O_2$}, perception of effort]). Although a variety of workload variables are reported throughout the literature, workload is typically quantified by multiplying the volume (e.g. duration, distance) of a given training session by the intensity (e.g. heart rate, speed, perception of effort) of that session (i.e. workload = volume x intensity [e.g. session duration x session perception of effort, or session duration x mean exercise heart rate]; Busso, *et al.*, 1997; Foster, 1997; Foster, *et al.*, 1996; Foster *et al.*, 1995; Foster & Lehmann, 1997; Wallace, Slattery, & Coutts, 2014). The recent use of external measures of workload that lack an intensity descriptor, for example bowling volumes (Hulin *et al.*, 2014) or absolute distance covered (Colby *et al.*, 2014), have resulted in workload being referred to more broadly as merely the amount of work completed (i.e. volume).

2.3.1.1 The fitness-fatigue model: Banister *et al.*, (1975) quantified workload by keeping detailed records of all types of training undertaken during the case study of an elite swimmer. These records involved arbitrarily rating the intensity of swimming sessions as follows; warming up and warming down periods (intensity = 1), endurance training of harder intensity-long duration (intensity = 2), and higher intensity speed training with rest pauses (intensity = 3). Distances covered during training were then reported in hundreds of metres (i.e. 14,000 metres = 140 units) and workload was quantified by multiplying the session distance (volume) by the session intensity (i.e. 140 units x intensity of 2 = 280 training units).

Banister *et al.*, (1975) demonstrated that higher workloads combined with adequate recovery could yield improvements in performance, demonstrated by improvements in the speed at which distances were swum. Moreover, Banister and colleagues developed a simple model stating that the performance of an athlete could be estimated as 'fitness' minus 'fatigue' (i.e. performance = fitness – fatigue). In this model, 'fatigue' was expressed as the workload performed over the previous week (i.e. acute workload), whereas ‘fitness’ was expressed as the workload the athlete had been prepared for over the previous four-weeks (i.e. chronic workload). The size of acute workload relative to chronic workload provides an *“acute:chronic workload ratio”*, also commonly referred to as a “training-stress balance” (Hulin *et al.,* 2014). For example, when dividing acute workload by chronic workload, a result that is less than 1 indicates that acute workload is less than chronic workload and vice versa.

The arbitrary accumulation and decay of fitness and fatigue subsequent to the first, second, and third training stimulus is highlighted in Figure 2.1 (Banister & Calvert, 1980). This figure highlights that a training stimulus may generate twice as much fatigue as it does fitness, however subsequent to training the decay of fitness is somewhat longer than fatigue. One might expect optimal performance to occur at point A on the curves in Figure 2.1. This point is where training and fitness are at their highest. However, even though this indicates that the athlete is well trained, performance will be limited by residual fatigue incurred during previous training. Therefore, Banister’s modelling of acute and chronic workload states that the greatest gains in performance will be observed at point B, as this represents the greatest difference between fitness and fatigue (Banister & Calvert, 1980). These authors theorized that although higher workloads result in greater preparedness for performance, adequate rest and reductions in workload must be provided in order to dissipate residual fatigue from previous training (Banister & Calvert, 1980).

2.3.1.2 Training impulse (TRIMP): In addition to developing a model in which acute and chronic workloads could be monitored in order to predict performance (Banister & Calvert, 1980), Banister (1991) also developed a unit measure of training that attempted to quantify physical effort throughout a variety of training modalities. Specifically, Banister used changes in *heart rate* as a measure of intensity and training *duration* as a measure of volume (Banister, 1991). Moreover, attempting to guard against any bias toward long-duration exercise at low heart rate, fractional heart rate during exercise was multiplied by a scaling factor based on increases in blood lactate at high training intensities. For example, TRIMP is computed as, duration of training x [heart rate$_{exercise}$ – heart rate$_{rest}$ / heart rate$_{max}$ – heart rate$_{rest}$], which is then multiplied by a scaling factor (*y*). In this formula, *y* can be read directly from a curve when fractional elevation of exercise heart rate is known. As such, this scaling factor (*y*) accounts for increases in lactate as exercise intensity increases (Banister, 1991). The benefit of quantifying training in this scientific fashion allowed for one of the first unit measures of quantifying the training dose, as most evaluations of training had previously been performed from log books written in words or from coach's previous subjective experience in preparing athletes for competition (Banister, 1991).

The use of Banister's TRIMP as a method of quantifying training has several limitations; (1) an athlete may forget to use his or her heart rate monitor or a heart rate monitor may have a technical failure during training, resulting in a loss of workload data, (2) contact sports such as rugby league, and rugby union involve wrestling and heavy upper body collisions (Austin, Gabbett, & Jenkins, 2011a; Austin, Gabbett, & Jenkins, 2011b), which may cause heart rate monitors to become dislodged or damaged resulting in either lost or invalid data, and (3) the association between blood lactate and fractional elevation in heart rate is specific for each individual and requires routine laboratory testing, which may provide economical and logistical constants in a team sport environment.

2.3.1.3 Session rating of perceived exertion workload (s-RPE): In an attempt to address some of the aforementioned limitations of Banister's TRIMP, Foster *et al.*, (2001) investigated the relationship between heart rate and session rating of perceived exertion (RPE; modified from Borg, 1985). These two methods of quantifying training were compared during a controlled cycle ergometry protocol, and during practice sessions and competitive matches of a sub-elite basketball team. The session-RPE (s-RPE) method was quantified as training duration (min) multiplied by RPE, with participants providing an RPE, based on the global intensity of the session, from a category ratio scale 0-10 (Table 2.1) 30 minutes after the conclusion of the exercise bout. As an objective reference method for quantifying each exercise bout, the time spent in each of five heart rate zones (50-60%, 60-70%, 70-80%, 80-90%, and 90-100% of heart rate peak) was multiplied by the corresponding multiplier for each zone (50-60% = 1, 60-70% = 2, 70-80% = 3, 80-90% = 4, and 90-100% = 5) providing a workload score for each exercise bout (Edwards, 1998). The results demonstrated a strong correlation between the s-RPE method and summated heart rate zone method for continuous (cycle ergometry), and intermittent (basketball sessions) exercise. These results established that either method may be used to create a TRIMP score to quantify aerobic training in individual and team sports (Foster *et al.*, 2001).

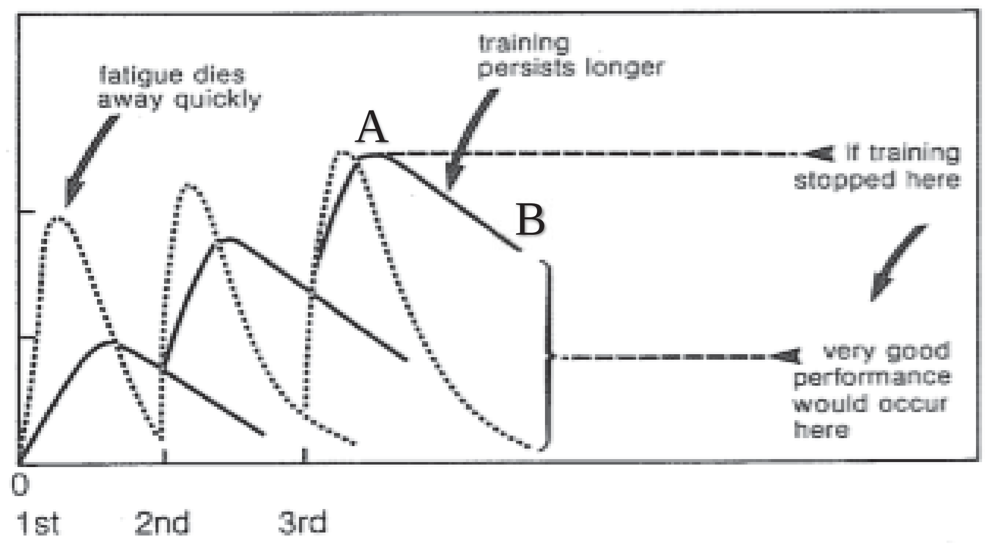

Figure 2.1. Shows the growth and decay of fitness (solid lines) and fatigue (dotted lines) in response to impulses of training on separate occasions. From Banister and Calvert (1980). NB: *y*-axis measured in arbitrary unit.

Table 2.1. Modification of the category ratio rating of perceived exertion (RPE) scale. Adapted from Foster *et al.*, (2001).

Modification of the category ratio rating of perceived exertion scale	
Rating	Descriptor
0	Rest
1	Very, very easy
2	Easy
3	Moderate
4	Somewhat hard
5	Hard
6	-
7	Very hard
8	-
9	-
10	Maximal

The practical, simple, inexpensive and non-invasive method of monitoring workload through the use of s-RPE has also been demonstrated as a valid indicator of global internal aerobic workload in team sports such as, soccer (Impellizzeri, *et al.,* 2004), and basketball (Coutts, *et al.,* 2003). However, anecdotal observations suggest that the subjectiveness of athletes rating the global intensity of prescribed sessions has resulted in circumspect interpretation of these data amongst practitioners. Furthermore, recent research has investigated relationships between injury rates and objective measures of workload quantified via global positioning systems (GPS) (Colby *et al.,* 2014; Gabbett & Ullah, 2012). Measures of total distance derived from GPS have shown strong correlations with measures of heart rate (r = 0.72-0.77; Scott *et al.,* 2013; Casamichana *et al.,* 2014), Banister's TRIMP (r = 0.73; Scott *et al.,* 2013), and s-RPE (r = 0.75-0.80; Scott *et al.,* 2013; Wallace *et al.,* 2014a). Additionally, the use of external cycling power output as a measure of workload has recently shown stronger correlation with total $\dot{V}O_2$ (r = 0.94), than Banister's TRIMP (r = 0.85), and s-RPE (r = 0.75), suggesting that external work is the most valid method of quantifying workload (Wallace *et al.,* 2014b).

2.3.1.4 Global positioning systems (GPS): Instantaneous measures of external workload can be measured with portable GPS units, which are commercially available to the public (Cummins, *et al.,* 2013). In brief, GPS is a satellite-based navigational tool that was designed and distributed for military purposes. The system is based on the emission of radio signals between the GPS receiver (worn on the subject) and over 20 satellites orbiting the earth (Schutz & Chambaz, 1997). The position and changes in position of the GPS receiver are measured by the lag time of radio signals sent between it and orbiting satellites. As these signals are sent at a known velocity (the speed of light), the subject's position, distance travelled and velocity can be calculated by trigonometry, which requires the receiver to be in contact with a minimum of three satellites at any time point (Schutz & Chambaz, 1997). Commercially available GPS receivers emit these radio signals at rates of one signal per second (1 Hz), five signals per second (5 Hz), and 10 signals per second (10 Hz).

2.3.1.5 GPS validity and reliability: The capability of practitioners to measure the activity profile of multiple players in real-time via GPS is an attractive concept. As such, sport scientists endeavouring to take and use these measurements should have an understanding of the error associated with doing so (Hopkins, 2000). The two most important aspects of measurement error are: (1) concurrent validity (i.e. the agreement between the observed value and the true value), and (2) retest reliability (i.e. the reproducibility of the observed value when the measurement is repeated) (Hopkins, 2000). Inevitably, error can be present in the true value itself, thus concurrent validity can be complex. Nevertheless, these fundamental aspects of determining the 'noise' (error) associated with a measure cannot be discounted. Furthermore, knowledge of the noise associated with a test allows for a rigorous interpretation of test results using the typical error of measurement to identify 'real' changes from 'technical and biological' error, which can be compared with a predetermined smallest worthwhile change (Batterham & Hopkins, 2006; Pyne, 2003). This approach also provides a rating of a test's ability to detect 'real' differences as either 'good', 'OK', or 'marginal', based on whether the smallest worthwhile change is greater than, equal to, or less than the typical error of measurement, respectively (Pyne, 2003; Pyne, 2013).

Valid and reliable measurement tools are not only essential for detecting meaningful changes in performance, but also injury risk. The ability to identify the effect of a potential risk factor (e.g. workload) depends on how accurately the factor can be measured (Bahr & Holme, 2003). Modifiable injury risk factors that can be subject to intervention by physical training or behavioural approaches should be easy to measure and with excellent precision. For example, an intraclass correlation coefficient (ICC) of 0.8 for test-retest reliability of a measure, would mean that the necessary sample size would increase by more than 50% relative to an ICC of 1.0 (i.e. $[1/0.8]^2 = 1.56$; Bahr & Holme, 2003). Considering that a prospective cohort study would require 200 injury cases in order to detect small associations with injury risk (Bahr & Holme, 2003), an increase of 56% would result in the need for 312 injury incidents. For example, previous studies by Orchard *et al.*, (1997), Bennell *et al.*, (1998), and Arnason *et al.*, (2003), which have investigated relationships with modifiable factors and injury risk in team sports, have used sample sizes of 37, 102, and 306, respectively, with injury frequency counts of 6, 12, and 31, respectively. As such, a requirement of an additional 56% of injury incidents, if measurement error were poor, could have significant consequences on statistical power (Batterham & Hopkins, 2006; Bahr & Holme, 2003).

Global positioning systems available to the public have shown greater accuracy (validity) and reliability at higher sampling frequencies (Jennings, *et al.*, 2010; MacLeod, Morris, & Nevill, 2009; Portas, *et al.*, 2010). Devices with sampling rates of 1 Hz have shown good accuracy for measuring total distance covered in a straight line while walking, jogging, running, and sprinting; the measured value overestimating criterion value by ~2% (Gray, *et al.,* 2010). Although the accuracy of measuring distance travelled is compromised when velocity increases and the path travelled is non-linear; 1 Hz GPS underestimates distance travelled by up to 10% (Gray, *et al.,* 2010; Glover, 2010). These findings have been supported by others (Portas, *et al.,* 2010) who also demonstrated that 1 Hz GPS units underestimate total distance covered on a multi-directional course by moderate and large differences (approximately 4-11%), however these differences can be reduced to small and trivial amounts (approximately 0-2%) when the sampling rate is increased to 5 Hz. Collectively these studies (Gray, *et al.,* 2010; Portas, *et al.,* 2010) demonstrate that both 1 Hz and 5 Hz GPS units can be used to quantify distances travelled in linear motion with acceptable accuracy, however more complex scenarios used by these authors, which involved sharp and multiple changes in direction are associated with questionable error at a sampling rate of 1 Hz.

However, Jennings and colleagues (2010) demonstrated that both 1 Hz and 5 Hz GPS units provide a valid measure of total distance during a different team sport running circuit. The circuit consisted of 140 m of running that involved; two maximal sprints, four sharp changes in direction over 10 m, three periods of walking, three periods of jogging, one striding effort and a deceleration to a complete stop. Validity was assessed using the standard error of estimate (SEE). The SEE is calculated as the standard deviation of the percentage difference between the known distance and the GPS recorded distance. The percentage difference between the known distance and GPS distance was also calculated as an indication of the direction and magnitude of bias, and error was express as the coefficient of variation (CV). The results demonstrated that both 1 Hz and 5 Hz GPS units are valid (SEE = 3.6% and 3.8% for 1 Hz and 5 Hz, respectively) and reliable (CV = 3.6%) for measuring total distance during the team sport running circuit. The acceptable accuracy of GPS to measure total distance has also been confirmed by others (Petersen, *et al.,* 2009; Rampinini *et al.,* 2015).

It has also been demonstrated that as distance travelled decreases and velocity increases, the accuracy and reliability of GPS for measuring distance decreases. Jennings *et al.,* (2010) highlighted that maximal sprints over 10 m, 20 m, and 40 m showed poor accuracy (SEE = 30.9%, 17%, and 11.9%, respectively) and reliability (CV = 39.5%, 23.0%, and 9.2%, respectively) for measuring distance with 5 Hz GPS. The findings of Jennings *et al.,* (2010) have been extended by others (Waldron, *et al.,* 2011), who demonstrated moderate validity for GPS to measure distance whilst accelerating over 10 m (CV = 8.1%), and 20 m (CV = 8.1%), however validity improved as distance travelled increased to 30 m (CV = 5.0%) (Table 2.2). Collectively, these findings (Jennings *et al.*, 2010; Waldron *et al.*, 2011) demonstrate the inability of both 1 HZ and 5 Hz GPS to identify short periods of rapid variations in speed, demonstrating that total distance measured over longer team sport bouts is a more accurate and reliable variable. The aforementioned studies may have methodical limitations, such as difficulties selecting criterion measures of distance or synchronising GPS data with criterion data. However, considering the detrimental effect on statistical power when determining modifiable injury risk factors with poor measurement error (Bahr & Holme, 2003), there is no available knowledge, which demonstrates that any variable other than total distance covered is capable of producing a viable workload-injury relationship when using 5 Hz GPS.

2.3.2 Workload and injury relationship

The first study to investigate the relationship between workload and injury incidence in rugby league players was conducted in a semi-elite cohort and reported a strong positive relationship between s-RPE workload and injury incidence (r=0.86), suggesting that the risk of injury for these athletes increases as s-RPE workload increases (Figure 2.2, Gabbett, 2004a). It has also been demonstrated that reductions in pre-season s-RPE workloads result in reduced injury incidence, without compromising improvements in $\dot{V}O_{2max}$ (Gabbett, 2004b), demonstrating that there is an optimal workload that will illicit improvements in performance, without increasing injury likelihood.

Gabbett and Jenkins (2011) demonstrated that s-RPE workload was significantly correlated with the incidence of overall injury (r=0.82), non-contact field injury (r=0.82), and contact field injury (r=0.80) in elite rugby league players. These findings demonstrate that workload not only has a strong positive relationship with overall injury, but also contact, and non-contact injury independently. As such, a number of studies in rugby league have collectively grouped contact and non-contact injuries as one (King, *et al.*, 2010; Murray, *et al.*, 2014).

Table 2.2. Validity of measured distance and timing gate speed against GPS measurements.

	Measured distance/timing gate (mean ± s)	GPS measure (m) (mean ± s)	CV (%)	95% LOA	95% ratio LOA
Distance (m)					
10 m sprint	10 ± 0	9.07 ± 1.11^a	8.06	–	1.10 ×/÷ 1.29
20 m sprint	20 ± 0	17.91 ± 1.66^a	8.09	–	1.12 ×/÷ 1.21
30 m sprint	30 ± 0	27.98 ± 1.45^a	5.00	–	1.07 ×/÷ 1.11
Moving 10 m	10 ± 0	9.52 ± 0.68^a	4.81	–	1.05 ×/÷ 1.15
Speed ($km \cdot h^{-1}$)					
10 m sprint	16.52 ± 1.19	14.46 ± 1.94^a	9.81	2.05 ± 3.62	1.15 ×/÷ 1.30
20 m sprint	20.48 ± 1.15	18.28 ± 1.66^a	8.54	2.19 ± 3.34	1.12 ×/÷ 1.20
30 m sprint	22.73 ± 1.23	20.72 ± 1.43^a	6.61	2.01 ± 2.18	1.09 ×/÷ 1.11
Moving 10 m	27.02 ± 1.20	24.98 ± 1.97^a	5.68	–	1.08 ×/÷ 1.12

Note: CV = coefficient of variation; LOA = 95% limits of agreement; 95% ratio LOA = 95% ratio limits of agreement. [a]Significantly different ($P < 0.05$) from measured distance or timing gate speed. Moving 10m = speed between timing gate at 20m and timing gate at 30m. From Waldron, Worsfold, Twist, & Lamb (2011).

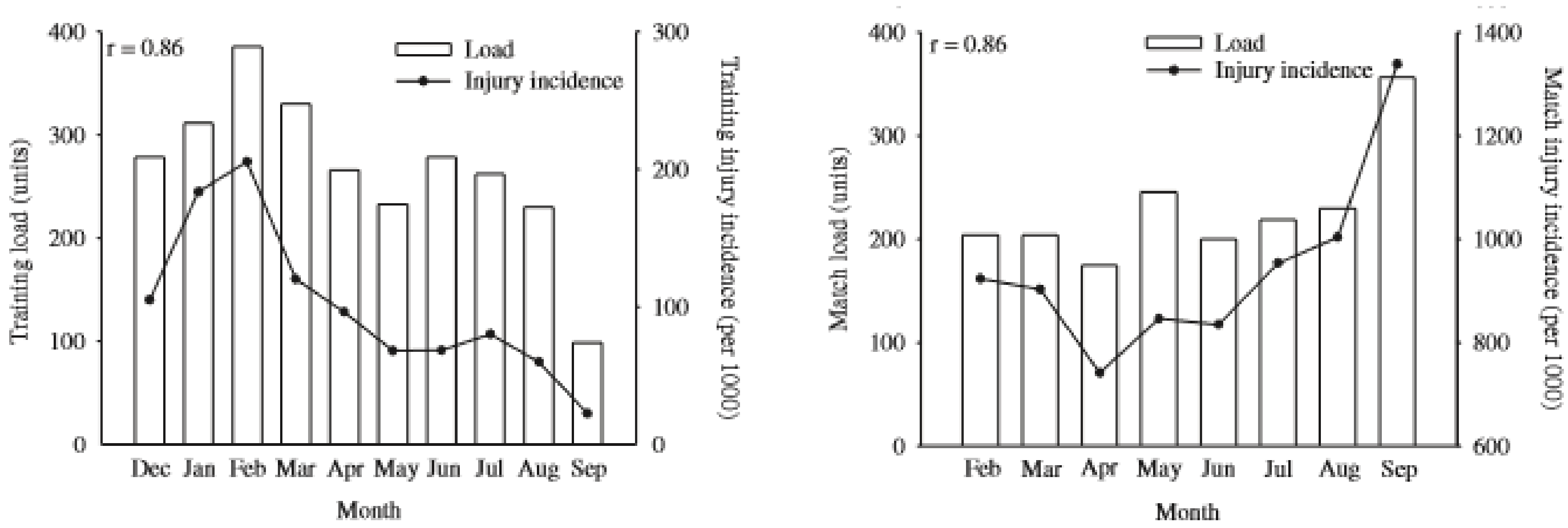

Figure 2.2. Influence of training workload on training injury incidence (left), and the influence of match workload on match injury incidence (right). From Gabbett (2004a).

The s-RPE model of workload has also been linked with injury in Australian football (Rogalski *et al.*, 2013), rugby union (Cross *et al.*, in press), cricket (Hulin *et al.*, 2014) and basketball (Anderson, *et al.*, 2003). Specifically, higher workloads (Gabbett, 2010; Gabbett & Jenkins, 2011), and sudden increases in workload (Anderson, *et al.*, 2003; Hulin *et al.*, 2014; Rogalski, *et al.*, 2013) are associated with increased injury risk.

Session-RPE has been combined with the use of the fitness-fatigue model to investigate injury likelihoods in elite cricket fast bowlers (Hulin *et al.*, 2014). Hulin and colleagues (2014) showed that injury risk increased significantly with an acute:chronic workload ratio >1.5, with three-fold (external workload) and four-fold (internal workload) increases in injury risk when the acute:chronic workload ratio was greater than 2.0 (Figure 2.3). Additionally, Hulin and colleagues (2014) highlighted that increases in the likelihood of sustaining an injury occurred one-week subsequent to acute workload being greater than chronic workload, whereas no relationships were found between the acute:chronic workload ratio and injury risk in the week that the workload was recorded. These findings demonstrate the delayed effect of "spikes" in workload on injury risk, which may be related with remaining fatigue from cricket match-play (McNamara *et al.*, 2013). To date, these methods of investigating workload-injury relationships have not been applied in rugby league players.

Global positioning systems (GPS) were recently used in the first study to investigate relationships between running workloads and the risk of lower body soft-tissue injury in elite rugby league players (Gabbett & Ullah, 2012). The results demonstrated that the manipulation of the volume and intensity of running workloads can lead to increases, and decreases in injury risk. Specifically, greater amounts of very high-intensity (>7 m·s^{1}) running were associated with an increased risk of lower body soft-tissue injury during rugby league training sessions. Moreover, players that covered greater distances at very low (0-1 m·s^{1}), low (1-3 m·s^{1}), and moderate (3-5 m·s^{1}) intensities had a lower risk of injury than players that covered less distance at these intensities (Gabbett & Ullah, 2012). However, these finding should be interpreted with caution, as 5 Hz GPS devices used in this investigation.

Global positioning systems have also been used to investigate injury risk relative to cumulative workload over chronic periods in elite Australian football (Colby, *et al.*, 2014). These authors demonstrated an "inverse U shaped" relationship with cumulative three-week workloads.

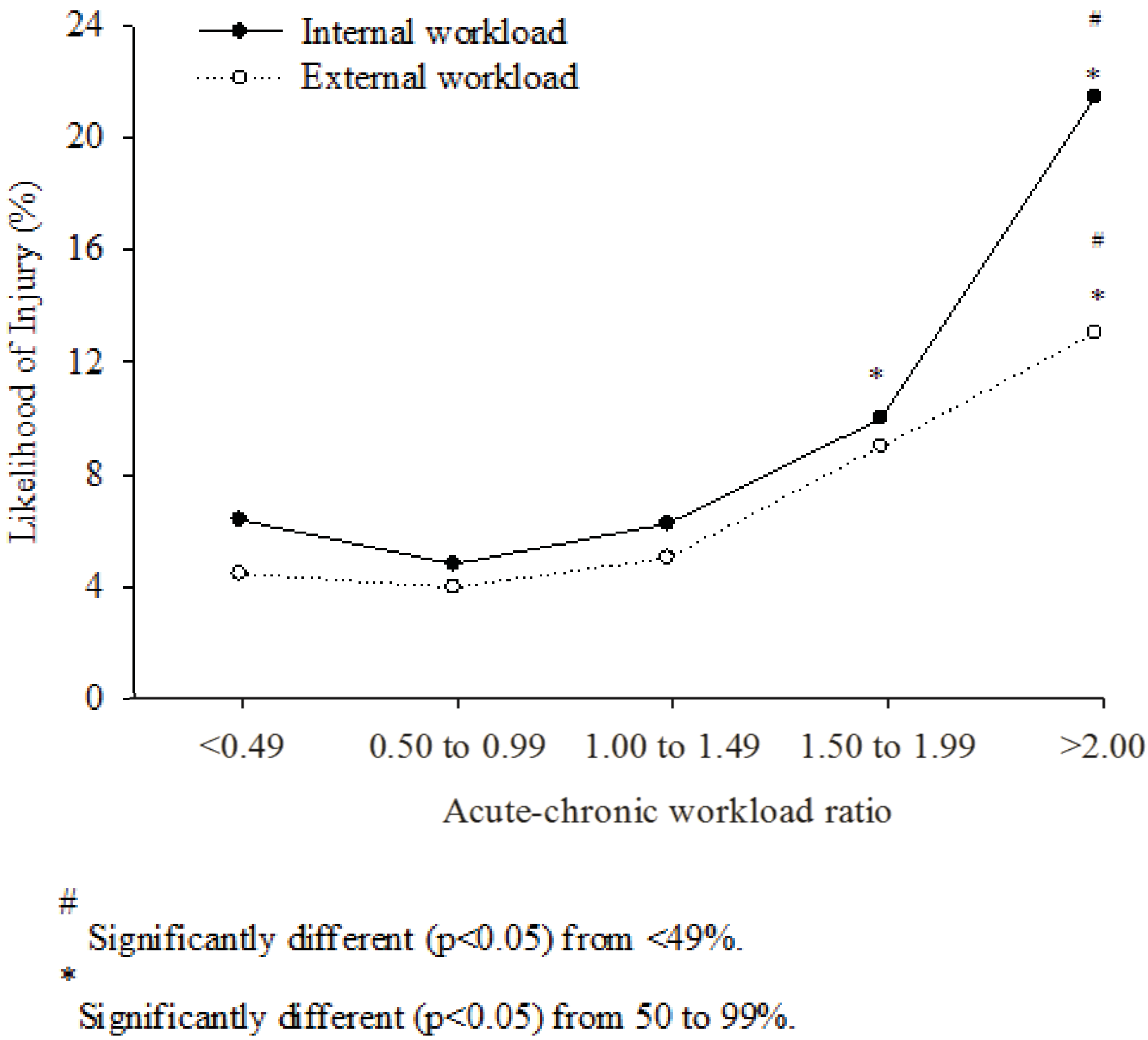

Figure 2.3. Likelihood of injury in the subsequent week to acute:chronic workload ratios. From Hulin, *et al.*, (2014).

Specifically, compared with players that covered <73.7 km over a three-week period, players that covered between 73.7 and 86.6 km had a 5-fold increase in the likelihood of sustaining and injury; however, covering >86.6 km was not associated with a greater risk of injury than covering <86.6 km over three weeks (Colby, *et al.*, 2014). The findings of Colby *et al.*, (2014) contrast those of Cross *et al.*, (in press), who demonstrated a "U shaped" relationship between cumulative four-week workloads and injury risk. That is, rugby union players with cumulative four-week s-RPE workloads >8,652 arbitrary units (AU) had a greater risk of injury than players between 5,933 and 8,651 AU, but not an increased risk of injury when compared with players <3,684 AU. These findings collectively demonstrate that injury risk does not consistently increase as chronic workload increases; suggesting that chronic workload alone is not the greatest predictor of workload-injury relationships.

Other investigations in rugby league have demonstrated that players with greater physical qualities, such as well-developed maximal speed, $\dot{V}O_{2max}$ (Gabbett & Domrow, 2005), prolonged high-intensity running ability, and upper body strength (Gabbett, Ullah, & Finch, 2012) have a reduced risk of injury. These are all physical qualities that are known to improve after increases in training workloads (Bartolomei, *et al.*, 2014; Daussin, 2007; Tønnessen *et al.*, 2011). Together, the above mentioned studies provide evidence that: (1) training workloads can have positive and negative influences on injury risk in elite team sport athletes and (2) although the addition of GPS to team sports has offered valuable insight into injury likelihoods, only a limited number of studies have used GPS to investigate workload-injury relationships. As such, there is a paucity of evidence predicting injury rates with the use of this technology.

2.4 SUMMARY

Relationships exist between workload and injury risk in elite rugby league players. Excessive s-RPE workloads are linked with greater injury likelihoods (Gabbett, 2004a; Gabbett, 2004b), and players with greater physical characteristics such as, upper body strength, and prolonged high-intensity running ability have a greater probability of completing matches injury free (Gabbett, Ullah & Finch, 2012). However, while it has been demonstrated that preparedness for competition grows as chronic workloads outweigh acute workloads (Banister *et al.*, 1984), and that injury risk increases as acute workloads outweigh chronic workloads (Hulin *et al.*, 2014), these methods have not been applied to assess the likelihood of injury in high-intensity, intermittent team sports. As such, there is currently a void of scientific literature surrounding the knowledge of the effect of acute and chronic workloads and GPS workloads on the likelihood of injury in elite rugby league players.

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SECTION A: STUDY ONE

PURPOSE AND AIMS

The purpose of the first study within this thesis is to extend upon the existing knowledge of workload-injury relationships by investigating if the comparison of acute and chronic workloads is an appropriate model for predicting injury in elite rugby league players. A novel aspect of this research will be insight into the relationship between injury risk and an external measure of workload, quantified via GPS (GPSports, SPI-HPU, Canberra, Australia, 5 Hz [interpolated 15 Hz]). The GPS equipment used in this thesis has to ability to accurately and reliably measure total distance covered (Petersen et al., 2009; Rampinini et al., 2015). As such, this variable will be used as the criterion value for workload during all training sessions and matches for an elite rugby league team throughout two consecutive seasons. In comparison with one season, multiple seasons allows for a greater probability of the sample containing at least 200 injury cases, which is required to detect small changes in the risk of sustaining an injury when exposed to one modifiable injury risk factor (Bahr & Holme, 2003).

Significance of the research

From a practical perspective, this research will provide further insight into predicting the likelihood of injury during seasonal rugby league training and competition with the use of GPS technology. As such, practitioners developing and implementing training programs in elite rugby league will have further knowledge of the influence that training and match workloads have on injury risk over acute, and chronic periods.

Experimental hypotheses

In light of previous investigations of acute and chronic workloads on injury risk in cricket fast bowlers (Hulin *et al.*, 2014), it was hypothesised that;

- Acute:chronic workload ratios >1.5 will result in an increased risk of injury, compared with ratios less than 1.0
- The acute:chronic workload ratio would provide greater injury prediction than acute, and chronic workload in isolation

CHAPTER THREE: THE ACUTE:CHRONIC WORKLOAD RATIO IS PREDICTIVE OF INJURY

The acute:chronic workload ratio is predictive of injury: high chronic workload may decrease injury risk in elite rugby league players

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Keywords: Team sport; Workload; Training load; Injury; GPS

3.1 INTRODUCTION

Injuries commonly occur in team sports (Dvorak *et al.*, 2011; Gabbett, 2003; Gabbett, 2004; Orchant *et al.,* 2010) and negatively influence team success in domestic and continental competitions (Árnason *et al.*, 2004; Eirale *et al.*, 2013; Hägglund *et al.*, 2013). High training and match-play workloads have been shown to increase injury likelihood in team sports (Gabbett, 2004a; Rogalski *et al.*, 2013). However, physical qualities such as higher aerobic capacity, prolonged high-intensity running ability, and greater body mass index decrease the probability of athletes sustaining an injury (Gabbett & Domrow, 2005; Gabbett, Ullah & Finch, 2012; Grant *et al.*, 2015). These physical qualities improve with increases in workload, presenting practitioners with the challenge of identifying the optimal workload that improves fitness, without increasing the likelihood of injury (Bartolomei *et al.*, 2014; Daussin *et al.,* 2007; Tønnessen *et al.,* 2011; Schoenfeld *et al.,* 2015).

Workload-injury investigations in team sports typically quantify workload in absolute terms, for example the workload performed in a week versus injury (Gabbett, 2004a; Rogalski *et al.,* 2013; Colby *et al.*, 2014). However, *workload-performance* investigations have examined absolute workload performed in one week (referred to as acute workload) relative to four-week chronic workload (i.e. four-week average acute workload) (Banister *et al.,* 1975; 1980; 1984). The logic behind this comparison of workloads is the provision of a workload index, which provides an indication of whether the athlete's recent acute workload is greater, less than or equal to the workload that the athlete has been prepared for during the preceding chronic period. We refer to this method as the acute:chronic workload ratio.

Using this concept, Hulin *et al.*, recently demonstrated that the risk of cricket fast bowlers sustaining an injury increased three-fold when acute bowling workloads were two times greater than chronic bowling workloads, i.e. an acute:chronic workload ratio ≥2 (Hulin *et al.,* 2014). An additional finding of this study was that a higher chronic workload was protective against injury in the current, and subsequent weeks. However, the physical demands of cricket differ from many high-intensity, intermittent football codes (Cummins *et al.,* 2013). This model, which compares the magnitude of acute workload relative to chronic workload has not been used to investigate the workload-injury relationship in a team sport other than cricket. Furthermore, no study has investigated the influence of changes in acute workload when players have been exposed to either high or low chronic workloads. Therefore, it is unknown whether players with a high chronic workload are more, or less resistant to changes in acute workload.

Injury-workload relationships have typically been examined by categorising workload data into weekly blocks and investigating injury-workload relationships within that week (Gabbett, 2004; Rogalski *et al.*, 2013; Colby *et al.*, 2014). A limitation of this approach is that a change in acute workload between two weeks (e.g. between the Wednesday of one week and the Wednesday of the following week) could potentially over-, or underestimate the likelihood of injury. A simple method of nullifying this potential bias could be to average the workload completed in the current week with that completed in the previous week (i.e. 2-week average workload). This method may also provide insight into the effect of consecutive weeks of either high or low workloads on injury risk.

Contemporary workload monitoring in team sports involves the use of global positioning systems (GPS) (Johnston *et al.*, 2015; Hulin *et al.*, 2015; Hulin & Gabbett, 2015). However, comparisons of GPS variables with injury risk are limited (Colby *et al.*, 2014; Gabbett & Ullah, 2012). To our knowledge, no research has investigated if the comparison of acute and chronic workloads derived from GPS is associated with injury in either the current week, subsequent week, or as an average over two weeks, in elite team sport athletes. Therefore, our aims were to investigate: (1) whether distance covered, measured by GPS and calculated as an acute:chronic workload ratio predicted injury and (2) the influence of the acute:chronic workload ratio on injury risk when players were exposed to either a high or low chronic workload.

3.2 METHODS

3.2.1 Participants

Fifty-three players (mean ± SD age, 23.4 ± 3.5 yr) from one elite rugby league club participated in this study over two Australian National Rugby League seasons. Of the two seasons, 20 (38%) participants competed in both seasons and 33 (62%) participants competed in one season –

equating to a total of 73 individual seasons of rugby league. Each season consisted of a 13 week pre-season period followed by 27 weeks of competition. All participants provided written consent and received a clear explanation of the study. All experimental procedures were approved by the Institutional Review Board for Human Investigation.

3.2.2 Quantifying workload

Workload was defined as absolute total distance (m) covered during all field training sessions and matches and was measured via GPS (GPSports, SPI-HPU 5-Hz [interpolated 15-Hz], Canberra, Australia). The GPS equipment used in this study is accurate and reliable for measuring total distance covered (Petersen *et al*, 2009; Rampinini *et al.*, 2015). This equipment presents challenges when measuring accelerations, decelerations, high-speed running, and collisions (Buchheit *et al.*, 2014; Johnston *et al.*, 2014; Gabbett, 2013; Rampinini, *et al.*, 2015). Therefore, total distance was the only variable included in this study (Bahr & Holme, 2003). In the event that a player did not wear a GPS unit or the GPS unit failed to collect data (<4% of the dataset), the player was given either the average workload of their positional group (training sessions) or their average match workload over the season (Colby *et al.*, 2014).

Our analysis included all field training sessions and matches throughout the 2013 and 2014 Australian National Rugby League seasons. A total of 8,177 individual files consisting of 6,777 training session files and 1,400 match files were used in this study.

3.2.3 Definition of injury

Injury records were updated and maintained by the club's senior physiotherapist. An injury was defined as any time-loss injury that resulted in a player being unable to complete full training or missing match time (King *et al.*, 2010). The inclusion of contact and non-contact injuries is consistent with previous research in rugby league, and is in line with the injury definition used by the governing body of Australian National Rugby League (Gabbett, 2004; Gabbett & Domrow, 2005; Gabbett & Jenkins, 2011).

3.2.4 Data analysis

The first and second aims of this study were investigated by categorising data into weekly blocks from Monday to Sunday. One-week total distance covered represented acute workload. Chronic workload was calculated as the four-week rolling average acute workload. Skewness and kurtosis indices were explored using SPSS and data demonstrated normal distribution. The acute:chronic workload ratio was calculated by dividing the acute workload by the chronic workload – providing the relative size of acute workload compared with chronic workload. A value of greater than 1 represents an acute workload greater than chronic workload and vice versa. Workload classifications consisting of very-low through very-high were created according to z-scores (Economos *et al.*, 2007; Ma *et al.*, 2014). These classifications are displayed in Table 3.1.

Training weeks in which players performed a chronic workload below a z-score of -2 (very-low) were removed from the analysis of acute:chronic workload ratios (Hulin *et al.*, 2014). This removal equated to 3.8% of the dataset (86 of 2292 individual training weeks). This was performed so that a small increase in acute workload at very-low chronic workload would not be considered. That is, a player being subjected to an acute workload of 3,000 m, whilst having a chronic workload of 1,000 m, would be a very-low (2,000 m) increase in workload; however, it would be expressed as a very-high acute:chronic workload ratio (Hulin *et al.*, 2014). These very-low workloads remained in the dataset for the independent comparison of injury with absolute workloads.

The second aim of the present study was to investigate injury risk relative to the acute:chronic workload ratio when chronic workload is high, and when chronic workload is low. As such, chronic workloads were dichotomised by the median score (16,095 m) and injury-workload relationships between acute:chronic workload ratios combined with high, and low chronic workloads were calculated. The median split technique used in this study is in accordance with previous research in applied sport medicine (Johnston *et al.*, 2015).

Table 3.1. Workload classifications and boundaries for: (A) acute workloads, (B) chronic workloads, (C) acute:chronic workload ratios overall, and (D) acute:chronic workload ratios combined with low (<16,095 m), and high (>16,095 m) chronic workloads.

(A) Acute workload	*z-score*	*Current & Subsequent week (m)*	*Two-week average (m)*
Very-low	≤ -2.00	≤ 3,268	≤ 5,020
Low	-1.99 to -1.00	3,269-9,624	5,021-10,351
Moderate-low	-0.99 to -0.01	9,625-16,000	10,352-15,668
Moderate-high	0.00 to 0.99	16,001-22,364	15,669-20,966
High	1.00 to 1.99	22,365-28,797	20,967-26,265
Very-high	≥ 2.00	≥ 28,798	≥ 26,266
(B) Chronic workload		*Current & Subsequent week (m)*	*Two-week average (m)*
Very-low	≤ -2.00	≤ 6,955	≤ 6,675
Low	-1.99 to -1.00	6,956-11,343	6,676-11,074
Moderate-low	-0.99 to -0.01	11,343-15,729	11,075-15,526
Moderate-high	0.00 to 0.99	15,730-20,116	15,527-19,995
High	1.00 to 1.99	20,117-24,503	19,996-24,449
Very-high	≥ 2.00	≥ 24,504	≥ 24,450
(C) Acute:chronic workload ratio		*Current & Subsequent week*	*Two-week average*
Very-low	≤ -2.00	≤ 0.30	≤ 0.45
Low	-1.99 to -1.00	0.31-0.66	0.46-0.74
Moderate-low	-0.99 to -0.01	0.67-1.02	0.75-1.01
Moderate	0.00 to 0.99	1.03-1.38	1.02-1.30
Moderate-high	1.00 to 1.99	1.39-1.74	1.31-1.58
High	2.00 to 2.99	1.75-2.10	1.59-1.87
Very-high	≥ 3.00	≥ 2.11	≥ 1.88
(D) Acute:chronic workload ratio		*Combined with low chronic workload*	*Combined with high chronic workload*
Very-low	≤ -2.00	≤ 0.30	≤ 0.66
Low	-1.99 to -1.00	0.31-0.66	0.67-0.84
Moderate-low	-0.99 to -0.01	0.67-1.02	0.85-1.01
Moderate	0.00 to 0.99	1.03-1.37	1.02-1.18
Moderate-high	1.00 to 1.99	1.38-1.74	1.19-1.35
High	2.00 to 2.99	1.75-2.16	1.36-1.53
Very-high	≥ 3.00	≥ 2.17	≥ 1.54

3.2.5 Statistical analysis

The risk of injury ± 90% confidence interval (CI) was calculated for the week that the workload occurred (current week), the following week (subsequent week), and for the average workload over the current and previous week (two-week average). Injury risks were calculated as the number of injuries sustained relative to the number of exposures to each workload classification (Hulin *et al.*, 2014; Bahr & Holme, 2003). Null-hypothesis testing was conducted using a binary logistic regression model with injury/no injury as the dependent variable. Acute workload, chronic workload, and acute:chronic workload ratios were independently modelled as predictor variables. Relative risk (RR) ×/÷ 90% CI were calculated to determine which workload variables increased (RR >1) or decreased (RR <1) the risk of injury (Bahr & Holme, 2003). Due to the inability of RR to provide ± 90% CI, the square root of upper CI/lower CI provided a ×/÷ 90% CI (Hopkins *et al.*, 2007).

Results of clinical and practical significance can be overlooked due to non-significant (p>0.05) null-hypothesis tests, which fail to adequately deal with the real-world importance of an effect (Batterham & Hopkins, 2006; Hopkins *et al*, 2009). As such, the p value derived from binary logistic regression and the value of the RR between groups were used to calculate the probabilities that the true effect was harmful, trivial and beneficial (Hopkins *et al.*, 2007). These values were reported in quantitative and qualitative terms according to the following: ≥5%, unlikely; ≥25%, possibly; ≥75%, likely; ≥95%, very likely (Batterham & Hopkins, 2006; Hopkins *et al*, 2009). Practical significance occurred when the probability that the true effect was either harmful or beneficial was ≥75%, likely (Hopkins *et al*, 2009).

3.3 RESULTS

A total of 205 injuries (20.2 per 1,000 hours) were recorded. The most common sites of injury were the thigh (23.4%), knee (13.2%), and ankle (11.7%).

3.3.1 Acute, and chronic workloads

In the current week, a very-high acute workload (≥ 28,798 m) was associated with an increased risk of injury, compared with all other acute workloads (RR range from 1.9-13.9 ×/÷ 1.9-2.2;

likelihood range = 86-98%, likely–very likely), Table 3.2. There were no differences in injury risk among any chronic workload categories (RR range from 0.6-1.3 ×/÷ 1.0-15.8; likelihood range = 16-63%, unlikely–possibly), Table 3.3.

3.3.2 Acute:chronic workload ratio

In the current week, a very-high acute:chronic workload ratio (≥ 2.11) was associated with an injury risk that was: (i) 6.9 times greater than a very-low ratio of ≤0.30 (RR = 6.9 ×/÷ 1.7; likelihood = 98%, very likely), (ii) 3.4 times greater than a low ratio of 0.31-0.66 (RR = 3.4 ×/÷ 2.0; likelihood = 97%, very likely), (iii) 2.3 times greater than a moderate ratio of 1.03-1.38 (RR = 2.3 ×/÷ 3.4; likelihood = 91%, likely), and (iv) double that of a high ratio of 1.75-2.10 (RR = 2.0 ×/÷ 17.2; likelihood = 77%, likely), Table 3.4.

Table 3.2. Relationships between acute workload and the risk of injury (± 90% CI) during the current week, subsequent week, and with two-week average acute workloads. Data bars represent injury risk on a scale of 0 to 40%.

			Current week		Subsequent week		Two-week average	
Acute workload	Current & Subsequent week (m)	Two-week average (m)	Risk of injury (%)	± 90% CI	Risk of injury (%)	± 90% CI	Risk of injury (%)	± 90% CI
Very-low[¥μ]	≤ 3,268	≤ 5,020	1.5	2.4	8.0	5.2	2.2	2.5
Low[ϕ]	3,269-9,624	5,021-10,351	6.0	2.2	10.3	2.8	5.8	2.3
Moderate-low	9,625-16,000	10,352-15,668	9.9	1.9	6.9	1.7	8.8	1.8
Moderate-high	16,001-22,364	15,669-20,966	8.4	1.5	11.0	1.8	9.2	1.6
High[γ]	22,365-28,797	20,967-26,265	8.0	2.3	6.9	2.2	8.0	2.4
Very-high[*]	≥ 28,798	≥ 26,266	18.8	16.1	0.0	0.0	6.3	10.0

* Very likely (≥95%) greater injury risk in the current week than very-low and low, and likely (≥75%) greater injury risk in the current week than moderate-low through high;

¥ Likely (≥75%) decreased risk of injury than low in the current week and very likely (≥95%) decreased risk of injury than low through very-high in the current week;

γ Very likely (≥95%) and likely (≥75%) decreased risk of injury in the subsequent week compared with moderate-high and low;

μ Likely (≥75%) decreased risk of injury than two-week average categories low, moderate-high and high

μ Very likely (≥95%) decreased risk of injury than moderate-low and very-high two-week average;

ϕ Likely (≥75%) decreased risk of injury than two-week average acute workload categories moderate-low and moderate-high.

Table 3.3. Relationships between chronic workload and the risk of injury (± 90% CI) during the current week, subsequent week, and with two-week average chronic workloads. Data bars represent injury risk on a scale of 0 to 40%.

			Current week		Subsequent week		Two-week average	
Chronic workload	Current & Subsequent week (m)	Two-week average (m)	Risk of injury (%)	± 90% CI	Risk of injury (%)	± 90% CI	Risk of injury (%)	± 90% CI
Very-low	≤ 6,955	≤ 6,675	4.7	3.7	8.9	5.3	6.6	4.7
Low	6,956-11,343	6,676-11,074	8.6	3.2	8.8	3.3	8.1	3.1
Moderate-low	11,343-15,729	11,075-15,526	10.8	1.9	9.2	1.8	9.4	1.8
Moderate-high	15,730-20,116	15,527-19,995	7.8	1.6	8.7	1.7	8.7	1.6
High	20,117-24,503	19,996-24,449	8.5	2.6	7.4	2.4	8.5	2.5
Very-high	≥ 24,504	≥ 24,450	0.0	0.0	9.1	14.3	0.0	0.0

Table 3.4. Relationships between acute:chronic workload ratios and the risk of injury (± 90% CI) in the current and subsequent weeks, and with two-week average acute:chronic workload ratios. Data bars represent injury risk on a scale of 0 to 40%.

	Acute:chronic workload ratio		Current week		Subsequent week		Two-week average	
Category	Current & Subsequent week	Two-week average	Risk of injury (%)	± 90% CI	Risk of injury (%)	± 90% CI	Risk of injury (%)	± 90% CI
Very-low[¥]	≤ 0.30	≤ 0.45	2.4	2.8	1.2	2.0	0.0	0.0
Low	0.31-0.66	0.46-0.74	5.0	2.5	8.9	3.4	7.6	3.1
Moderate-low	0.67-1.02	0.75-1.01	10.2	1.9	7.8	1.6	8.9	1.6
Moderate	1.03-1.38	1.02-1.30	7.2	1.5	7.8	1.6	6.9	1.6
Moderate-high[γ]	1.39-1.74	1.31-1.58	10.9	3.6	10.5	3.7	13.0	4.3
High[ϕ]	1.75-2.10	1.59-1.87	8.3	7.6	8.1	7.4	11.8	7.4
Very-high[*#]	≥ 2.11	≥ 1.88	16.7	14.4	11.8	12.9	16.7	14.4

* Very likely (≥95%) greater risk of injury than low, and very-low in the current week. Likely (≥75%) greater injury risk than moderate and high in the current week;

\# Likely (≥75%) greater risk of injury than low, moderate-low and moderate two-week average;

¥ Very likely (≥95%) and likely (≥75%) decreased risk of injury in the current and subsequent week than all other acute:chronic workload ratios;

ϕ Likely (≥75%) greater risk of injury than a moderate two-week average;

γ Very likely (≥95%) and likely (≥75%) increased risk of injury compared with low, moderate-low and moderate two-week average.

A very-high two-week average acute:chronic workload ratio (≥1.88) was associated with a risk of injury that was: (i) 2.2 times greater than a low ratio of 0.46-0.74 (RR = 2.2 ×/÷ 4.9; likelihood = 87%, likely), (ii) 1.9 times greater than a moderate-low ratio of 0.75-1.01 (RR = 1.9 ×/÷ 5.5; likelihood = 83%, likely), and (iii) 2.4 times greater than a moderate ratio of 1.02-1.30 (RR = 2.4 ×/÷ 3.0; likelihood = 92%, likely), Table 4. In the subsequent week, a very-high acute:chronic workload ratio demonstrated a 10-fold increase in injury risk compared with a very-low ratio (RR = 9.8 ×/÷3.6; likelihood = 97%, very likely), Table 3.4.

A high chronic workload (>16,095 m) combined with a very-high two-week average acute:chronic workload ratio (≥1.54) was associated with a greater risk of injury than a high chronic workload combined with the following workload ratios: low (0.67-0.84 [RR = 3.0 ×/÷ 4.3; likelihood = 92%, likely]), moderate-low (0.85-1.01 [RR = 3.8 ×/÷ 2.3; likelihood = 96%, very likely]), moderate (1.02-1.18 [RR = 4.6 ×/÷ 1.8; likelihood = 98%, very likely]), moderate-high (1.19-1.35 [RR = 4.0 ×/÷ 2.6; likelihood = 96%, very likely]), and high (1.36-1.53 [RR = 2.4 ×/÷ 16.3; likelihood = 82%, likely]), Table 3.5.

A low chronic workload (<16,095 m) combined with a very-high two-week average acute:chronic workload ratio (≥2.17) was associated with greater injury risks than a low chronic workload combined with the following workload ratios: low (0.31-0.66 [RR = 2.3 ×/÷ 9.8; likelihood = 84%, likely]), moderate-low (0.67-1.02 [RR = 1.8 ×/÷ 13.5; likelihood = 75%, likely]), moderate (1.03-1.37 [RR = 2.0 ×/÷ 11.7; likelihood = 79%, likely]), and high (1.75-2.16 [RR = 3.1 ×/÷ 55.5; likelihood = 81%, likely]), Table 3.5.

Table 3.6 displays the differences in injury risk among acute:chronic workload ratios combined with high chronic workloads, and low chronic workloads.

Table 3.5. Relationships among risk of injury (± 90% CI) and two-week average acute:chronic workload ratios combined with low (<16,095 m) chronic workload, and high (>16,095 m) chronic workload. Data bars represent injury risk on a scale of 0 to 40%.

	Low chronic workload			High chronic workload		
Category	Acute:chronic workload ratio	Risk of injury (%)	± 90% CI	Acute:chronic workload ratio	Risk of injury (%)	± 90% CI
Very-low	≤ 0.30	0.0	0.0	≤ 0.66	0.0	0.0
Low	0.31-0.66	7.8	4.1	0.67-0.84	9.6	4.1
Moderate-low	0.67-1.02	10.0	2.5	0.85-1.01	7.5	2.2
Moderate	1.03-1.37	9.3	2.6	1.02-1.18	6.2	2.2
Moderate-high	1.38-1.74	11.0	4.9	1.19-1.35	7.1	4.0
High	1.75-2.16	5.9	7.3	1.36-1.53	12.0	10.7
Very-high	≥ 2.17*	18.2	14.9	≥ 1.54**	28.6	18.1

* Likely (≥75%) greater risk of injury than a low chronic workload combined with a low, moderate-low, moderate, and high acute:chronic workload ratios.

** Very likely (≥95%) greater risk of injury than high chronic workload combined with moderate-low, moderate, and moderate-high acute:chronic workload ratios.

Table 3.6. Relative risk (RR ×/÷ 90% CI) of injury for high chronic workload combined with acute:chronic workload ratios (top row), compared with low chronic workload combined with acute:chronic workload ratios (left column). Data bars represent relative risk on a scale of 0.1 to 5.0.

Chronic workload / Acute:chronic workload ratio	High / Very-low		High / Low		High / Moderate-low		High / Moderate		High / Moderate-high		High / High		High / Very-high	
	RR	×/÷ 90% CI	RR	×/÷ 90% CI	RR	×/÷ 90% CI	RR	×/÷ 90% CI	RR	×/÷ 90% CI	RR	×/÷ 90% CI	RR	×/÷ 90% CI
Low / Very-low	0	>100	0	>100	0	>100	0	>100	0	>100	0	>100	0	>100
Low / Low	0	>100	1.2	6.7	1.0	6.3	0.8	5.6	0.9	10.2	1.5	14.9	3.7	**3.0
Low / Moderate-low	0	>100	1.0	4.6	0.8	*1.9	0.6	*1.4	0.7	3.8	1.2	15.1	2.9	*4.0
Low / Moderate	0	>100	1.0	4.8	0.8	2.5	0.7	*1.8	0.8	4.8	1.3	14.8	3.1	*3.5
Low / Moderate-high	0	>100	0.9	6.2	0.7	*2.6	0.6	*1.8	0.6	*4.4	1.1	21.0	2.6	*6.2
Low / High	0	>100	1.6	156.8	1.3	24.4	1.1	147.7	1.2	163.2	2.0	113.3	4.9	*13.4
Low / Very-high	0	>100	0.5	*14.8	0.4	*6.7	0.3	*4.4	0.4	*8.1	0.7	49.7	1.6	56.2

** RR very likely (≥95%) different;

* RR likely (≥75%) different.

3.4 DISCUSSION

In this first study to investigate injury risk relative to the comparison of GPS derived acute and chronic workloads, we found that a ratio of acute and chronic workloads was predictive of injury in elite rugby league players. This ratio provides an indication of how the athlete's recent acute workload compares with the workload that the athlete has been prepared for during the preceding chronic period. We refer to this model as the acute:chronic workload ratio.

The value of our model is represented firstly by a very-high acute:chronic workload ratio demonstrating a greater risk of injury than all other workload ratios in the current week, subsequent week, and two-week average. Secondly, the relationships between injury risk and acute, and chronic workloads in isolation were less consistent. For example, a very-high acute workload was associated with an increased injury risk in the current week, yet no injuries were sustained in the subsequent week, and no injury-workload relationships were observed between a very-high two-week average acute workload and moderate-low to high two-week average acute workloads. Furthermore, no injury-workload relationships were found among any chronic workload categories. Collectively these findings demonstrate that the acute:chronic workload ratio is a greater predictor of injury than either acute or chronic workload in isolation.

A novel finding of this study was that a high chronic workload combined with moderate, and moderate-high workload ratios had a smaller risk of injury than a low chronic workload combined with several acute:chronic workload ratios. Others have demonstrated that rugby league players with greater aerobic capacity and prolonged high-intensity running ability have a decreased risk of injury (Gabbett & Domrow, 2005; Gabbett, Ullah & Finch, 2012). Potentially, players in the current study who achieved a higher chronic workload may have improved the physical qualities associated with decreased injury risk. Additionally, practitioners perceive increased fatigue, and low levels of fitness to be two of the most important factors that increase injury risk in team sport athletes (McCall *et al.,* 2014), and higher levels of fitness reduce post-match neuromuscular fatigue in rugby league players (Johnston *et al.,* 2015). Furthermore, chronic and acute workloads were originally compared as an estimate of the relative comparison between fitness and fatigue (Banister *et al.,* 1975; 1980; 1984). These authors did this by expressing 'fatigue' as the athlete's acute workload, whereas ‘fitness’ was expressed as chronic workload (Banister et al., 1975; 1980; 1984). When considering our findings, with a moderate acute:chronic workload ratio, acute workload (i.e. ‘fatigue’) is similar in size to chronic workload (i.e. ‘fitness’). Therefore, it may be expected that a moderate acute:chronic workload ratio combined with a high chronic workload (i.e. high ‘fitness’) was associated with a smaller risk of injury than a moderate acute:chronic workload ratio combined with a low chronic workload (i.e. low ‘fitness’).

The greatest risk of injury in this study was displayed when a high chronic workload was combined with a very-high acute:chronic workload ratio. Collectively, our findings highlight that compared with players that have a low chronic workload, players with a high chronic workload are: (1) more resistant to injury with moderate-low to moderate-high acute:chronic workload ratios and (2) less resistant to injury when exposed to large spikes in workload, i.e. acute:chronic workload ratios >1.5.

Our results are consistent with findings from cricket (Hulin *et al.*, 2014). In the present study, when players were subjected to a workload (i.e. acute workload) that was classified as ~two-fold greater than the workload in which they were accustomed (i.e. chronic workload), up to a ten-fold increase in the risk of injury occurred. These findings may seem intuitive and unsurprising to practitioners. However this study provides a method of, and threshold values for modelling acute and chronic workloads to predict the relative risk and likelihood of injury in elite rugby league players. Furthermore, the goal of conditioning athletes is to optimize performance and minimize injury risk (Herring *et al.*, 2015). The acute:chronic workload ratio has been linked with improvements in performance in an individual sport (Banister et al., 1975; 1980; 1984), and according to this study and others (Hulin *et al.*, 2014), is linked with injury risk in team sports. Collectively, the aforementioned studies and the present findings endorse that monitoring acute:chronic workload ratios should be mainstream practice in elite sport. However, this is currently not the case (Herring *et al.*, 2015).

Another novel aspect of this study is the provision of threshold values that can be used to prescribe acute workload in order to obtain a high chronic workload. Specifically, acute workload can be increased to ~two-fold of chronic workload without increasing injury risk in the current or subsequent week. However, if a very-high acute:chronic workload ratio (>2) is prescribed in the current week, or maintained as an average over two-weeks, the risk of injury is likely greater than if acute workload were increased by a ratio less than 2. Additionally, acute:chronic workload ratios as an average over two weeks should be monitored in comparison to whether chronic workload is high or low. Our findings suggest that increasing acute workload as an average over two-weeks by: (1) greater than ~1.5 relative to a high chronic workload, or (2) greater than ~2 relative to a low chronic workload, will result in an increased risk of injury in elite rugby league players.

This study has demonstrated useful associations between simple distance measures and injury risk in elite rugby league players. We suspect that more information may be available if accelerations, high-speed running, and collisions were accounted for, however accurate and reliable analysis of these variables is not possible with the GPS equipment used in this study (Buchheit *et al.,* 2014; Johnston *et al.,* 2014; Gabbett, 2013; Rampinini, *et al.,* 2015). As such, accurate predictions of injury risk when using these variables would not be possible (Bahr & Holme, 2003). Further research may address this limitation and expand on the knowledge we have provided, by using GPS equipment (e.g. Catapult, 10 Hz) that is capable of accurately and reliably measuring accelerations, high-speed running, and collisions (Johnston *et al.,* 2014; Rampinini, *et al.,* 2015; Gabbett, Jenkins & Abernethy, 2010). Additionally, total distance covered has demonstrated a strong correlation (r = 0.80) with session-RPE workload during high-intensity, intermittent team sport training (Scott *et al.,* 2013). Session-RPE workload also has a strong positive correlation with non-contact injury (r = 0.82) and contact injury (r = 0.80) in rugby league (Gabbett & Jenkins, 2011) and has been used to model acute:chronic workload ratios, which were associated with injury in elite cricket fast bowlers (Hulin *et al.,* 2014). These studies collectively suggest that although total distance does not incorporate all aspects of training, it is an appropriate measure of workload.

Although the findings of this study demonstrate that very-low, and low absolute workloads are associated with decreased injury risk, we are tentative to recommend that players are consistently exposed to these workloads. Rugby league players can be required to cover ~1,140 m during a 10 minute period of match-play, and 9,561 m in a full 80-minute match (Gabbett, Jenkins & Abernethy, 2012; Hulin *et al.,* 2015; Hulin & Gabbett, 2015). Therefore, very-low

(~2,500 m) and low (~6,000 m) weekly workloads would likely result in players being underprepared for the physical demands of match-play, which may in turn increase the risk of injury.

3.4.1 Conclusion

This is the first investigation of injury likelihoods relative to GPS derived acute and chronic workloads in elite rugby league players. We recognise that injuries may occur due to factors unrelated to workload (Hägglund, Waldén & Ekstrand, 2012). Nevertheless, our findings demonstrate that the acute:chronic workload ratio provides a better prediction of injury than absolute workload in isolation. For the first time, we have investigated the influence of this workload ratio combined with high or low chronic workload – demonstrating that higher chronic workload can protect against injury when acute workload is similar to chronic workload. However, a high chronic workload, combined with large spikes in acute workload demonstrated the greatest risk of injury in this study. Our results establish that the ratio of acute workload to chronic workload should be monitored during the current week and as an average over two weeks relative to either a high, or low chronic workload. Finally, the findings of this study demonstrate that monitoring the comparison of acute and chronic workloads should be mainstream practice in elite sport.

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SECTION B: STUDY TWO

PURPOSE AND AIMS

Evidence of whether the recovery time provided between matches influences injury risk in team sport athletes is equivocal (Carling *et al.,* 2012; Dellal *et al.,* 2015; Dupont *et al.,* 2010; Murray *et al.,* 2014). Workload prescription can influence injury risk, however no study has investigated the workloads that athletes are subjected to in combination with between-match recovery time – this may potentially be a contributing factor to the ambiguous findings in relation to differences in the incidence of injury during congested and non-congested fixture periods. Therefore, the purpose of study two of this thesis was to investigate the risk of sustaining an injury when players were subjected to very-low through very-high workloads, relative to short (<7 days) and long (≥7 days) between-match recovery times. Additionally, the relationship among injury risk, chronic workloads and acute:chronic workload ratios were investigated during <7 day and ≥7 day between-match recovery times.

Significance of the research

In team sports, the recovery time between matches is dictated by a governing body. As such, between-match recovery time is a non-modifiable injury risk factor. However, workload is an injury risk factor that practitioners have the ability to modify. Therefore, this research aims to provide further insight into predicting and therefore modifying, the likelihood of injury during seasonal rugby league competition with the use of GPS technology. Practitioners developing and implementing training programs in elite rugby league will have further knowledge of the influence that training and match workloads have on injury risk over acute, and chronic periods and during non-modifiable between-match recovery times.

Experimental hypotheses

Considering the findings of study one and previous literature, it was hypothesised that:

- Injury risk is greater during shorter between-match recovery times
- Higher chronic workloads provide a reduced risk of injury during shorter between-match recovery times
- Provided that high acute:chronic workload ratios (i.e. ~1.5-2.0) are not prescribed, higher workloads can be achieved between matches without increasing injury risk

CHAPTER FOUR: COMBINED INFLUENCE OF BETWEEN-MATCH RECOVERY TIME AND WORKLOAD ON INJURY RISK IN ELITE RUGBY LEAGUE PLAYERS

Combined influence of between-match recovery time and workload on injury risk in elite rugby league players

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Keywords: Team sport; Workload; Training load; Injury; GPS, Recovery

4.1 INTRODUCTION

The likelihood of sustaining an injury in team sport can be influenced in part by: (1) the workloads that athletes are subjected to (Gabbett & Jenkins, 2011; Hulin *et al.,* 2014; Rogalski *et al.,* 2013), or (2) the recovery time that is provided between matches (Dupont *et al.,* 2010). Three to five days recovery time is required for match-induced reductions in neuromuscular and endocrine function to return to pre-match values in team sport athletes (Cormack, Newton & McGuigan, 2008; McLellan, Lovell & Gass, 2011). Consequently, during the shortest between-match recovery times in rugby league (five and six days), when training and preparation between matches is congested, there can be a greater incidence of injury than during longer between-match recovery times (Murray, Gabbett & Chamari, 2014). However, not all studies support the notion that congested fixture periods are associated with higher injury incidence in other team sports (Carling, Le Gall & Dupont, 2012; Dellal, Lago-Peñas & Rey, 2015). The equivocal evidence in relation to shorter between-match recovery times and increased injury risk may be due to the fact that previous studies have not investigated the workloads that athletes are subjected to between matches (Carling, Le Gall & Dupont, 2012; Dellal, Lago-Peñas & Rey, 2015; Dupont *et al.*, 2010; Murray, Gabbett & Chamari, 2014). That is, higher workloads can occur during longer between-match recovery times (Moreira *et al.,* 2015) and higher workloads or abrupt increases in workloads can increase injury risk (Gabbett & Jenkins, 2011; Hulin *et al.,* 2014; Rogalski *et al.*, 2013). However, no study has investigated the combined influence of workloads and between-match recovery time on injury incidence in elite team sport athletes.

Regardless of the recovery time between matches, workload-performance investigations have demonstrated that higher acute (i.e. one-week) internal workloads are associated with greater success in an elite team sport (Aughey, *et al.*, 2015). However, when acute workload exceeds chronic workload (i.e. four-week average acute workload), resulting in an acute:chronic workload ratio >1.0, a greater probability of losing more matches is observed (Aughey, *et al.,* 2015). It may seem surprising that regardless of between-match recovery time, higher acute workloads are related with winning more matches. However, higher acute workloads provide greater opportunity for coaches to implement skill-based strategic training, potentially resulting in a greater probability of winning the subsequent match. Although this may seem attractive to practitioners, further knowledge of the relationship amongst acute and chronic workloads, between-match recovery time and the risk of sustaining an injury is required. Furthermore, whether these higher acute internal (s-RPE) workloads were the result of higher external workloads, or the result of increased stress, travel or other off-field commitments in unknown.

Hulin *et al.*, (Chapter 3) recently demonstrated that acute and chronic external workloads can have both positive and negative influences on injury risk in elite rugby league players. When players have an acute:chronic workload ratio of 0.85-1.36, higher chronic workloads (>16,095 m) are associated with a smaller risk of injury than lower chronic workloads (<16,095 m). Conversely, a large spike in acute workload relative to chronic workload (i.e. acute:chronic workload ratios of 1.5 and 2.0) can result in a three- to five-fold increase in injury risk in elite team sport athletes (Hulin *et al.*, 2014; Hulin *et al.*, Chapter 3). However, it is currently not known: (1) whether higher chronic workloads are protective of injury or (2) the influence of abrupt increases in acute workload, during different between-match recovery times in elite team sport. Therefore, the purpose of this study was to investigate the risk of sustaining an injury when players were subjected to very-low through very-high workloads, during short (<7 days) and long (≥7 days) between-match recovery times. Additionally, the relationship among injury risk and chronic workloads and acute:chronic workload ratios were investigated during the same between-match recovery times.

4.2 METHODS

4.2.1 Participants

Thirty-five players (mean ± SD age, 24.3 ± 3.7 yr.) from one elite rugby league club participated in this study over two Australian National Rugby League (NRL) seasons. This study was conducted over the competition phase of each season (2 x 27 weeks). Players received a clear explanation of the study and written consent was obtained. Experimental procedures were approved by the Institutional Review Board for Human Investigation.

4.2.2 Injury definition

Injury records were updated and maintained by the club's senior physiotherapist. An injury was defined as any time-loss injury that resulted in a player being unable to complete full training, or missing match time (Hulin *et al.*, Chapter 3; King *et al.*, 2010). The inclusion of contact and non-contact injuries is consistent with previous research in rugby league, and is in line with the injury definition used by the governing body of Australian National Rugby League (Gabbett, 2004; Gabbett & Domrow, 2005; Gabbett & Jenkins, 2011).

4.2.3 Data analysis

Workload was defined as absolute total distance (m) covered during all field training sessions (n = 155) and matches (n = 52) and was measured via GPS (GPSports, SPI-HPU 5-Hz [interpolated 15-Hz], Canberra, Australia). The GPS equipment used in this study has demonstrated adequate accuracy and reliability for measuring total distance covered (Petersen *et al*, 2009; Rampinini *et al.*, 2015), however caution is advised when using this equipment to measure changes in velocity (Petersen *et al*, 2009; Buchheit *et al*, 2014) high-speed running (Petersen *et al*, 2009; Johnston *et al*., 2014), and collisions (Gabbett, 2013). As such, these variables were excluded from the analysis. In the event that a player did not wear a GPS unit or the GPS unit failed to collect data (<1% of the dataset), the player was given either the average workload of their positional group (training sessions) or their average match workload over the season (Colby *et al.*, 2014).

Between-match workloads were calculated as the total distance covered during all field training sessions and the subsequent match workload. Data were categorised into between-match recovery times comparable with previous studies (Murray *et al.*, 2014; Moreira *et al.*, 2015). Specifically, these recovery times consisted of <7 days (5 and 6 days) between matches, or ≥7 days (7, 8, and 9 days) between matches. Chronic workloads and acute:chronic workload ratios were calculated in accordance with previous studies (Hulin *et al.*, 2014; Hulin *et al.*, Chapter 3). Briefly, data from Monday to Sunday represented the acute workload, while the four-week rolling average acute workload represented the chronic workload. An acute:chronic workload ratio greater than 1 represented an acute workload greater than chronic workload and vice versa (Hulin *et al.*, 2014; Hulin *et al.*, Chapter 3). Further workload subdivisions were created based on z-scores as follows: (1) very-low, (2) low, (3) moderate, (4) high, and (5) very-high (Hulin *et al.*, Chapter 3). These five categories were created for <7 day, and ≥7 day between-match recovery times and are displayed in Table 4.1. Injury-workload relationships were calculated amongst very-low through very-high acute:chronic workload ratios, between-match workloads, and chronic workloads.

4.2.4 Statistical analysis

Injury risks were calculated as the total number of injuries sustained relative to the total number of exposures to each workload classification (Bahr and Holme, 2003; Hulin *et al.,* 2014; Hulin *et al.*, Chapter 3). Null-hypothesis testing was conducted using a binary logistic regression model with injury/no injury as the dependent variable. Between-match workloads, chronic workloads, and acute:chronic workload ratios were independently modelled as predictor variables. Relative risk (RR) ×/÷ 90% CI was calculated to determine which workload variables increased or decreased the risk of injury (Bahr & Holme, 2003). A RR of greater or less than 1 implied an increased or decreased risk of injury, respectively.

Statistical analysis was performed in accordance with recommended progressive statistics for studies in sports medicine and similar investigations (Hopkins *et al.,* 2009; Hulin *et al.,* Chapter 3). The *p* value derived from binary logistic regression and the value of the RR between groups were used to calculate the probabilities that the true effect was harmful, trivial, and beneficial (Hopkins *et al.,* 2009; Hopkins, 2007). These values were reported in quantitative and qualitative terms according to the following: <1%, almost certainly not; ≥1%, very unlikely; ≥5%, unlikely; ≥25%, possibly; ≥75%, likely; ≥95%, very likely; ≥99%, almost certainly (Hopkins *et al.,* 2009; Hopkins, 2007). Practical significance occurred when the probability that the true effect was either harmful or beneficial was ≥75%, likely (Hopkins *et al.,* 2009).

Table 4.1. Workload classifications and boundaries for: between-match workloads, chronic workloads, and acute:chronic workload ratios during <7 day and ≥7 day between-match recovery times. NB: z-score cut-offs are: Very-low (<-1.5), Low (-1.5 to -0.5), Moderate (-0.5 to 0.5), High (0.5 to 1.5), Very-high (>1.5).

(A) Between-match workload	< 7 day between-match recovery time (m)	≥ 7 day between-match recovery time (m)
Very-low	≤ 8,578	≤ 11,162
Low	8,579-12,833	11,163-15,818
Moderate	12,834-17,059	15,819- 20,545
High	17,060-21,276	20,546 - 25,200
Very-high	≥ 21,276	≥ 25,201
(B) Chronic workload	< 7 day between-match recovery time (m)	≥ 7 day between-match recovery time (m)
Very-low	≤ 9,985	≤ 10,358
Low	9,986-13,891	10,359-14,283
Moderate	13,892-17,920	14,284-18,578
High	17,921-21,871	18,579-22,772
Very-high	≥ 21,872	≥ 22,773
(C) Acute:chronic workload ratio	< 7 day between-match recovery time	≥ 7 day between-match recovery time
Very-low	≤ 0.75	≤ 0.87
Low	0.75-1.05	0.88-1.12
Moderate	1.06-1.36	1.13-1.38
High	1.37-1.66	1.39-1.62
Very-high	≥ 1.67	≥ 1.63

4.3 RESULTS

A total of 59 injuries (17.7/1000 training and match-play hours) were recorded over the course of two competitive seasons. The risk of injury was greater with <7 days than ≥7 days between matches (RR = 1.5 ×/÷ 1.5; likelihood = 91.1%, likely), Figure 4.1.

4.3.1 Between-match workloads

Figure 4.2A depicts the risk of injury with very-low through very-high between-match workloads during <7 day, and ≥7 day between-match recovery times. High and very high between-match workloads were not associated with a greater injury risk than lower workload categories, during either between-match recovery time (RR range from 0.0-1.1; likelihood range from 16-40%, possibly-unlikely).

4.3.2 Chronic workloads

With <7 days recovery between matches, a very-high chronic workload (≥21,872 m) was associated with a decreased risk of injury, compared with chronic workloads that were very-low (≤9,985 m [RR = 0.3 ×/÷ 5.4; likelihood = 86%, likely]), low (9,986-13,891 m [RR = 0.4 ×/÷ 5.2; likelihood = 77%, likely]), and moderate (13,892-17,920 m [RR = 0.3 ×/÷ 4.8; likelihood = 85%, likely]), Figure 4.2B. Also during <7 day between-match recovery times, a high chronic workload (17,921-21,871 m) was associated with a decreased risk of injury compared with chronic workloads, very-low (RR = 0.4 ×/÷ 2.5; likelihood = 95%, very likely), low (RR = 0.5 ×/÷ 2.2; likelihood = 89%, likely), and moderate (RR = 0.4 ×/÷ 1.9; likelihood = 99%, very likely), Figure 4.2B.

High and very-high chronic workloads combined with <7 days between matches had a smaller risk of injury than low chronic workload during ≥7 day between-match recovery times (RR range from 0.4-0.5 ×/÷ 4.2-12.7; likelihood range from 75-85%, likely), Figure 4.2B. During ≥7 day between-match recovery times, a low chronic workload (10,359-14,283 m) had a greater risk of injury than moderate (14,284-18,578 m [RR = 4.1 ×/÷ 2.7; likelihood = 98%, very likely]), and high chronic workloads (18,579-22,772 m [RR = 1.9 ×/÷ 2.4; likelihood = 83%, likely]), Figure 4.2B.

4.3.3 Acute:chronic workload ratio

During <7 day between-match recovery times, a very-high acute:chronic workload ratio (≥1.67) was associated with an increased risk of injury when compared with acute:chronic workload ratios very-low (≤0.75) through high (1.37-1.66 [RR range from 2.7-5.3 ×/÷ 1.2-2.7; likelihood range from 94-99%, likely-almost certainly]). A very-high acute:chronic workload ratio (≥1.67) combined with <7 days recovery between matches was also associated with a greater risk of injury than low (0.88-1.12) through high (1.39-1.62) acute:chronic workload ratios during ≥7 day between-match recovery times (RR range from 2.8-10.3 ×/÷ 1.0-4.0; 88-100%, likely-almost certainly), Figure 2C.

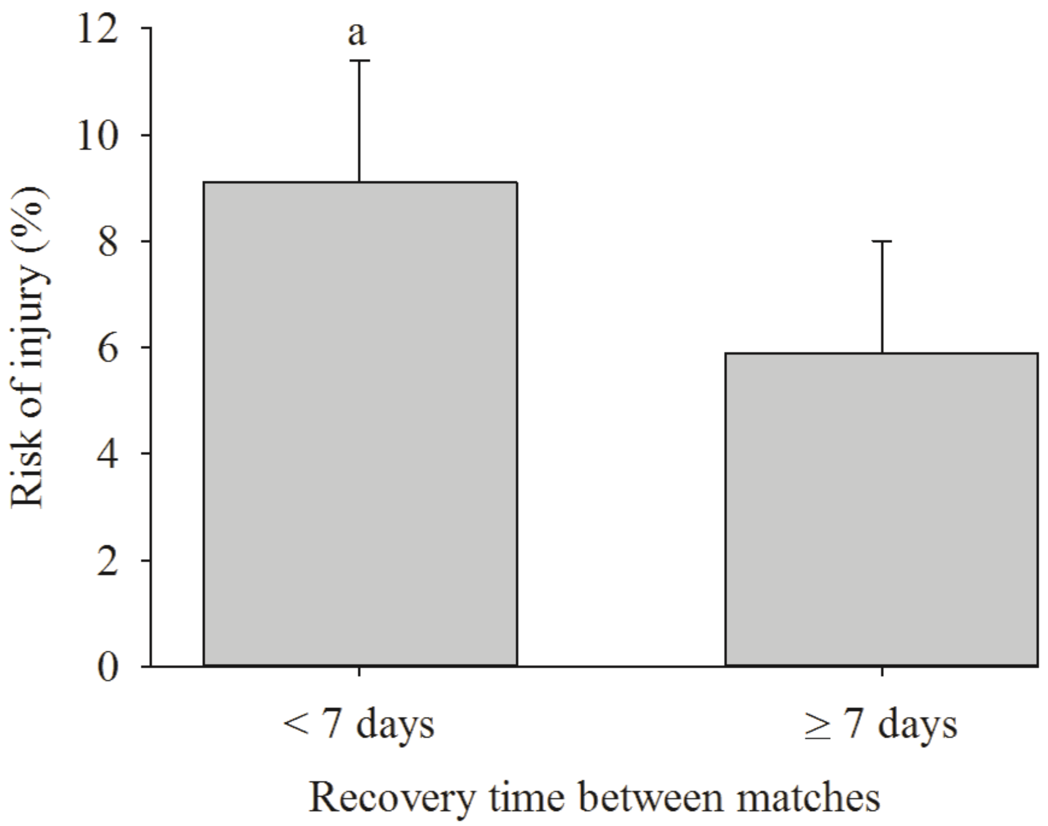

Figure 4.1. Risk of injury ± 90% CI during between-match recovery times of <7 days, and ≥7 days.

[a]Likely (≥75%) greater injury risk than ≥7 day between-match recovery time.

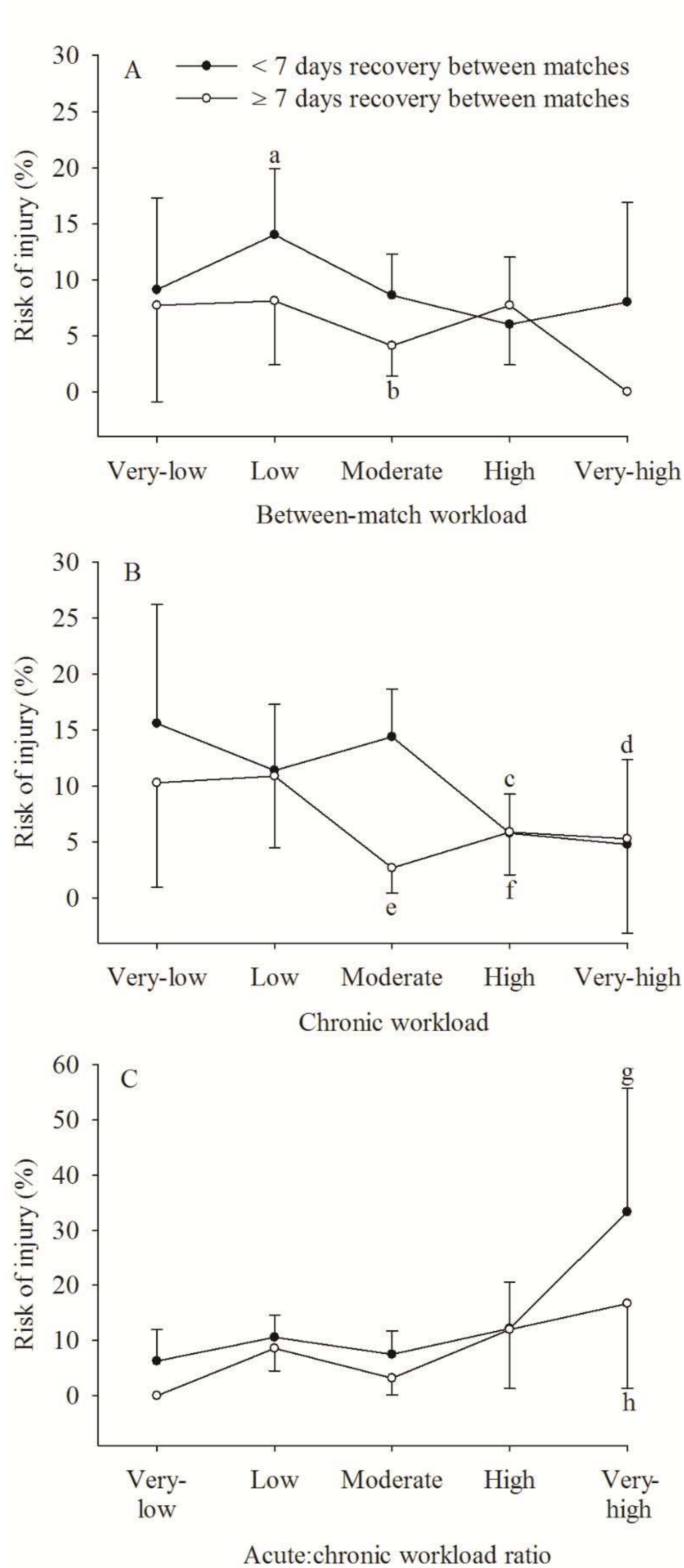

Figure 4.2. Risk of injury ± 90% CI during between-match recovery times of <7 days, and ≥7 days combined with between-match workloads (A), chronic workloads (B), and acute:chronic workload ratios (C).

Figure 4.2 (Continued).

[a] Very likely (≥ 95%) different from high between-match workload during <7 day between-match recovery time.

[b] Likely (≥ 75%) different from high, and low between-match workload category during ≥7 day between-match recovery time.

[c] Very likely (≥95%) different from very-low and moderate chronic workloads and likely (≥75%) from low chronic workload during <7 day between-match recovery time. Likely (≥75%) from very-low and low chronic workloads during ≥7 day between-match recovery time.

[d] Likely (≥75%) different from very-low, low, and moderate chronic workloads during <7 day between-match recovery time. Likely (≥75%) different from low chronic workload during ≥7 day between-match recovery time.

[e] Very likely (≥95%) different from very-low and low chronic workloads during ≥7 day between-match recovery time. Almost certainly (≥99%) different from very-low to moderate chronic workloads during <7 day between-match recovery times.

[f] Likely (≥75%) different from low chronic workload during ≥7 day between-match recovery time. Likely (≥75%) different from very-low to moderate chronic workloads during <7 day between-match recovery times.

[g] Almost certainly (≥99%) different from moderate acute:chronic workload ratio, very likely (≥95%) different from acute:chronic workload ratios very-low and high; Likely (≥75%) different from low acute:chronic workload ratio, during either between-match recovery time.

[h] Likely (≥75%) different from moderate acute:chronic workload ratio during ≥7 day between-match recovery times.

4.4 DISCUSSION

This study demonstrated that the risk of elite rugby league players sustaining an injury is greater with <7 days than ≥7 days between matches. However, these novel findings collectively demonstrate that the manipulation of a controllable factor (workload) can either increase or decrease the injury risk associated with non-modifiable between-match recovery time. Specifically, regardless of between-match recovery time, high chronic workloads demonstrated a decreased risk of injury compared with low and very-low chronic workloads. High and very-high chronic workloads during <7 day between-match recovery times were associated with a ~40-70% lower risk of sustaining an injury compared with low and very-low chronic workloads during either between-match recovery time. Additionally, a very-high acute:chronic workload ratio combined with <7 days recovery between matches was associated with the greatest risk of injury.

In this study, the two greatest risks of injury were observed when players had a very-high acute:chronic workload ratio combined with <7 days (33.3% injury risk) or ≥7 days (16.7% injury risk) recovery between matches. Additional injury risk factors in this study, were when players had a moderate to very-low chronic workloads during <7 day between-match recovery times (11.4-15.6% injury risk) and low to very-low chronic workloads combined with ≥7 days recovery between matches (10.3-10.9% injury risk). These findings, which demonstrate that lower chronic workloads and sudden spikes in workload increase the risk of injury may be related. That is, a high chronic workload may reduce the risk of injury due to the protection it provides against a very-high acute:chronic workload ratio. For example, chronic workloads of 19,000 m and 12,000 m would be classed as high and low, respectively. Therefore, an acute workload greater than 20,000 m would result in a moderate (i.e. 1.05) and very-high (i.e. 1.67) acute:chronic workload ratios for athletes with high and low chronic workloads, respectively. Therefore, higher chronic workloads provide protection against a spike in acute workload, which was associated with the greatest risk of injury in this study and others (Hulin *et al.*, 2014; Hulin *et al.*, Chapter 3).

Higher between-match workloads were not associated with an increased risk of injury in this study. Moreover, no injuries were sustained when players completed very-high workloads during ≥7 day between-match recovery times. Furthermore, provided that high acute:chronic workload ratios are not prescribed, previous research has shown that higher workloads between matches are associated with a greater number of victories in team sport (Aughey *et al.*, 2015). Collectively, these findings may be attractive to coaches and practitioners that are hoping to implement higher training workloads between matches. However, attention to the myriad of factors other than workload, which are related to injury risk and to the risk factors for overtraining and illness should also be considered when planning and prescribing between-match workloads (Hägglund, Waldén & Ekstrand, 2012;. Meeusen *et al.,* 2012). For example, although this study demonstrates that higher chronic workloads have a smaller risk of injury than lower chronic workloads, it is likely that long-term excessive workload may result in non-functional over-reaching, characterised by decreases in performance and vigour and increased fatigue (Meeusen *et al.*, 2012). As such, we suggest that while attempting to increase and maintain high chronic workloads, attention is also paid to factors that increase the risk of overtraining and illness, such as travel, inadequate sleep, and a lack of recovery and training variation within each microcycle (Foster & Lehmann, 1998; Meeusen *et al.*, 2012).

Collectively, previous studies may support our findings that a high chronic workload can reduce the risk of injury. Specifically, Gabbett *et al.*, demonstrated that rugby league players with greater aerobic capacity, and prolonged high-intensity running ability have a lower risk of injury (Gabbett & Domrow, 2005; Gabbett, Ullah & Finch, 2012). Furthermore, only two weeks of low-volume sprint interval training is required to elicit improvements in team sport athletes' high-intensity, intermittent running ability and aerobic capacity (Macpherson & Weston, 2015). Therefore, considering that rugby league training and match-play involves sprinting efforts interspersed with low-intensity activity (Gabbett, Jenkins & Abernethy, 2012; Gabbett, 2012) the athletes in the current study that achieved a higher chronic workload may have improved or maintained these physical qualities and in turn decreased their risk of sustaining an injury. However, for chronic workloads to be increased and provide resistance to injury, acute:chronic workload ratios greater than 1 must be strategically prescribed at certain times throughout the season. The findings of this study suggest that the associated injury risk would be lower if chronic workloads were increased during ≥7 day between-match recovery times and if very-high acute chronic workload ratios (i.e. >1.6) were avoided.

Valid analysis of injury risk in relation to collisions, high-speed running, and accelerations is not possible with the GPS equipment used in this study (Buchheit *et al*, 2014; Johnston *et al.*, 2014; Petersen *et al*, 2009; Rampinini *et al.*, 2015). Although more information would be available if these variables were investigated, this study still provides useful and novel findings in relation to workload-injury relationships during various between-match recovery times in elite rugby league. Furthermore, injury risk in team sport athletes can also be attributed to multiple factors that have not been included in this study (Bahr & Holme, 2004; Hägglund, Waldén & Ekstrand, 2012). However, to achieve the statistical power required to investigate other factors such as, previous injury, age, physical fitness, in conjunction with the modifiable and non-modifiable injury risk factors in the present study, a considerably larger dataset comprising many teams over a number of seasons would be required (Bahr & Holme, 2004).

A significantly larger dataset would also be required to investigate injury risk in the subsequent week to the factors investigated in this study. Specifically, only data for players participating in two consecutive weeks of first-grade competition were included in this study. When players were removed from first-grade, or away on representative duty, they were exposed to a different between-match recovery time and were therefore excluded from the analysis until they returned and played two consecutive matches at first-grade level for the club in this investigation. This factor results in a smaller dataset when investigating the subsequent week. Because of this, this dataset cannot be analysed in the same fashion as the current week.

4.4.1 Conclusion

Original findings in relation to modifiable and non-modifiable injury risk factors have been provided by this study. Injury risk is greater during <7 day between-match recovery times than ≥7 day between-match recovery times; however workload can be manipulated to decrease the injury risk associated with a shorter recovery time between matches. For example, a higher chronic workload provides protection against a spike in acute workload, which was associated with the greatest risk of injury in this study. Furthermore, provided that very-high acute:chronic workload ratios are not prescribed, higher between-match workloads can be achieved without increasing injury risk in elite rugby league players. Additionally, due to commercial and sponsorship commitments, rugby league's governing body is unlikely to provide a between-match recovery time that is consistently seven days or more. As such, this study offers practitioners fresh insight of how a controllable factor (workload) can be modified in order to decrease injury risk during elite rugby league competition.

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CHAPTER FIVE: SUMMARY, FUTURE RESEARCH AND CONCLUSIONS

5.1 SUMMARY AND RECOMMENDATIONS FOR FUTURE RESEARCH

The work within this thesis is the first to investigate injury risk in relation to acute and chronic workloads derived from GPS in elite rugby league players. Both studies were conducted over two consecutive elite rugby league seasons and have provided novel findings. Simple distance measures were collected during all field-based training sessions and matches and subsequently calculated as acute (one-week) and chronic (four-week rolling average) workloads. In study one, acute workload was mapped against chronic workload to investigate the ability of the acute:chronic workload ratio to predict injury in the week that the workload occurred, the following week and as an average over two-weeks. The findings from study one agree with our experimental hypotheses. That is, the acute:chronic workload ratio is a greater predictor of injury than either acute or chronic workload alone. Furthermore, workload can have positive and negative influences on injury risk. Namely, compared with players that have a low chronic workload (<16,095 m), players with a high chronic workload (>16,095 m) are *more resistant to injury* with acute:chronic workload ratios of 0.85-1.36 and *less resistant to injury* with a very-high acute:chronic workload ratio (≥1.54), Table 3.6.

In study two the combined influence of between-match recovery time and workload on injury risk was investigated in the same cohort as study one. However, only the competition phase was investigated (i.e. pre-season training was excluded), resulting in a smaller sample size than study one. A unique aspect of this study was that injury risk was explored in comparison with the workload completed between matches. Specifically, workloads were quantified between the conclusion of one match to the conclusion of the subsequent match, during <7 day (5 and 6 day) and ≥7 day (7, 8 and 9 day) between match-recovery times. This study demonstrated that injury risk is 1.5 times greater during <7 day than ≥7 day between-match recovery times (Figure 4.1). However, injury risk was not increased with high and very-high between-match workloads (Figure 4.2A). High and very-high chronic workloads displayed a protective effect on injury risk regardless of the recovery time between matches (Figure 4.2B). Furthermore, a very-high acute:chronic workload ratio (~1.6) during <7 day between-match recovery times was associated with the greatest risk of injury (Figure 4.2C).

Although these studies provide useful and practically applicable information, there are some limitations that may advise future research. Speculatively, more information may be available if accelerations, high-speed running, and collisions could be accounted for and modelled in the same fashion as distance covered. However as mentioned throughout this thesis, only distance covered was able to be quantified in a valid manner, which is recommended for studies investigating injury risk factors (Bahr & Holme, 2003). Future research may address this limitation and expand on the knowledge we have provided, by using equipment that is capable of accurately and reliably measuring other demands associated with rugby league match-play. If these variables are quantified in a precise fashion then the relationships between acute and chronic high-speed running, and contact workloads may also be investigated in relation to injury risk.

The injury definition used in this thesis comprised time loss injuries, which is a common approach in team sport (Carling, McCall, Le Gall & Dupont, 2015; Hulin *et al.*, 2014; King *et al.*, 2009). Contact and non-contact injuries were investigated collectively, which is in agreement with previous studies (Gabbett, 2003; Gabbett, 2004; Murray, Gabbett & Chamari, 2014) and with the injury definition recommended for studies in rugby league, which is: *"Any pain or disability that occurs during participation in rugby league match or training activities"* (King *et al.*, 2010). Furthermore, s-RPE workload has a strong positive correlation with non-contact injury ($r = 0.82$) and contact injury ($r = 0.80$) in rugby league (Gabbett & Jenkins, 2011). Increased workload results in increased levels of fatigue, in the form of increased heart rate, blood lactate concentration and RPE and decreased physical performance (Gabbett, 2008). Increased levels of fatigue are coupled with reductions in tackling technique (Gabbett, 2008) and increased tackle related injuries (Gabbett, 2000; King & Gissane, 2009). Collectively, these studies suggest that workload is related with contact and non-contact injuries and both can be used to investigate workload-injury relationships. The advantage of combining these injury mechanisms is the provision of a greater number of injuries and therefore a greater probability of predicting small associations with injury risk (Bahr & Holme, 2003).

At least 200 injury cases are required in order to have the adequate statistical power to detect small changes in the risk of sustaining an injury, in comparison with one injury risk factor (Bahr & Holme, 2003). In study one of this thesis there were a total of 205 injuries, which comprised 73 contact, 46 non-contact, and 86 unknown injury mechanisms (see Appendix 1). As such, investigating either known contact or non-contact injury alone would not have provided the acceptable sample required to detect small associations with injury. Future studies will require multiple teams over a number of seasons in order to obtain a sample size that is large enough to relate the modifiable injury risk factors in this thesis with small adjustments in the risk of either contact or non-contact injury. Studies with a greater sample size would also be required to further investigate injury risk among factors such as playing position, age, previous injury and/or physical fitness in conjunction with the modifiable and non-modifiable injury risk factors used in this thesis (Bahr & Holme, 2003).

Resistance training is another modality that is coupled with field-based training in rugby league conditioning programs. Accounting for resistance training workloads may have provided additional information on workload-injury relationships. Quantifying the global intensity of resistance training sessions with the use of s-RPE has demonstrated viability comparable with aerobic training (Sweet *et al.,* 2004). Furthermore, s-RPE as a method for quantify resistance training sessions is more viable than total force production (Day *et al.*, 2004; McGuigan *et al.,* 2004; Sforzo & Touey, 1996; Simão, *et al.*, 2007; Sweet *et al.*, 2004). These studies suggest that s-RPE can be used to measure resistance training workloads. Unfortunately restrictions were imposed on the data collection procedures within this thesis. That is, the elite rugby league club that provided the participants for these studies was not willing to allow the collection of s-RPE workloads, due to circumspect interpretation of the subjective RPE scale, discussed in section 2.3.1.3. Future research may address this limitation by investigated injury likelihoods in relation to acute and chronic workloads derived from s-RPE during all modalities of training in rugby league.

5.2 CONCLUSION

Prior to the work presented within this thesis there was a paucity of information that related injury with external GPS workload in rugby league players. These findings provide preliminary evidence that acute and chronic workloads derived via GPS are associated with injury. Study one is the first investigation to provide threshold values for modelling acute and chronic workloads to predict the relative risk and likelihood of sustaining an injury in elite rugby league players. These findings were expanded in study two, which investigated the influence of these workload thresholds on injury risk during short and long between-match recovery times.

This thesis demonstrates that higher workloads exhibit positive and negative influences on injury risk in elite rugby league players. Predicting workload-injury relationships should be done through the comparison of the workload that the athlete has performed relative to the workload in which the athlete has been prepared. Moreover, injury risk is greater with <7 days than ≥ 7 days recovery between matches. However, workloads can be manipulated to decrease the injury risk associated with shorter recovery time between matches; higher chronic workloads may provide protection against injury. As such, practitioners should note that training preparation can decrease injury risk in elite rugby league players.

More information will be available with a greater sample size and better equipment, which is capable of measuring other demands associated with training and match-play workloads. However, these studies provide original information on predicting injury with: (1) an external measure of training and match-play workload that can be collected accurately in elite team sport and (2) a novel method of modelling acute and chronic workloads.

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APPENDICES

APPENDIX ONE: INJURY DATA DURING STUDY ONE

Appendix one. Site and mechanism of all injuries used in study one.

	Injury incidence		Injury mechanism i.e. contact, non-contact or unknown		
Site	Number of injuries (% of total injuries)	Total injury incidence (per 1000 hours)	Number of contact mechanism (% of total injuries)	Number of non-contact mechanism (% of total injuries)	Number of unknown mechanism (% of total injuries)
Abdomen	3 (1.5)	0.3	1 (0.5)	0 (0.0)	2 (1.0)
Ankle	24 (11.7)	2.4	11 (5.4)	4 (2.0)	9 (4.4)
Buttock and Pelvis	4 (2.0)	0.4	1 (0.5)	1 (0.5)	2 (1.0)
Chest	4 (2.0)	0.4	4 (2.0)	0 (0.0)	0 (0.0)
Elbow	2 (1.0)	0.2	2 (1.0)	0 (0.0)	0 (0.0)
Foot	9 (4.4)	0.9	1 (0.5)	1 (0.5)	7 (3.4)
Hand	6 (2.9)	0.6	5 (2.4)	0 (0.0)	1 (0.5)
Hip and Groin	15 (7.3)	1.5	1 (0.5)	4 (2.0)	10 (4.9)
Knee	27 (13.2)	2.7	12 (5.9)	6 (2.9)	9 (4.4)
Lower Leg	19 (9.3)	1.9	3 (1.5)	6 (2.9)	10 (4.9)
Lumbar Spine	13 (6.3)	1.3	1 (0.5)	2 (1.0)	10 (4.9)
Neck	7 (3.4)	0.7	6 (2.9)	0 (0.0)	1 (0.5)
Shoulder	22 (10.7)	2.2	17 (8.3)	0 (0.0)	5 (2.4)
Thigh	48 (23.4)	4.7	7 (3.4)	21 (10.2)	20 (9.8)
Upper Arm	1 (0.5)	0.1	0 (0.0)	1 (0.5)	0 (0.0)
Wrist	1 (0.5)	0.1	1 (0.5)	0 (0.0)	0 (0.0)
Total	205 (100.0)	20.2	73 (35.6)	46 (22.4)	86 (42.0)

APPENDIX TWO: SUBJECT INFORMATION PACKAGE

SUBJECT INFORMATION PACKAGE

AN OBJECTIVE ANALYSIS OF DATA AQUISITION SYSTEMS USED IN PROFESSIONAL SPORT TO PREDICT INJURY AND PERFORMANCE

RATIONALE

Rugby League players are often at high risk of injury and performance can be affected by the prescription of training (it may be not difficult enough to affect an exercise related adaption or too difficult such that maladaptation, overtraining and injury may occur). Thus, it is important that the coaching staff are able to make informed decisions regarding training prescription. Indeed this is the purpose of much of the information being collected during training and in competition.

PROJECT OBJECTIVES

Correspondingly, an academic masters by research study has been devised and this project aims to analyse data that is routinely collected by the Sport Science staff at the St. George Illawarra Dragons football club for relationships to performance (game related) and injury occurrence. For example, the data analysed as part of this project may include variables from global positioning systems (GPS) that you wear during games and in training. It may also include performance data, for example your one repetition maximum strength and player well-fare, for example, questionnaires such as the rating of perceived exertion. Consent to collect this data is taken as tacit considering the terms of you employment. You will not be asked to take part in any additional assessments that are not required by the Sport Science staff at St. George Illawarra Dragons.

You should be aware that the data that collected may be presented in thesis, conference proceedings or in journal articles. However you will not be identified in any of these publications. Every effort will be made to avoid collection of irrelevant data. You are however free to withdraw your consent the data will not be used as part of the analysis for the research thesis, and or in publication, and any such request will not affect the terms of your employment with the St. George Illawarra Dragons Rugby League Football club.

INQURIES

Questions concerning the procedures, or rationale used in this investigation are welcome at any time. Please ask for clarification of any point that you feel has not been explained to your satisfaction, the persons you should discuss with during data collection are Mr Billy Hulin, Mr John Davey and Mr Andrew Gray. Should you have any concerns, your initial contact person is the investigator conducting this project, Dr John Sampson (School of Health Sciences, University of Wollongong: 02-4221-5597). If you have any further concerns or complaints about the conduct of this research, please contact the Ethics Unit on 02-4221-4457, or send an electronic mail to rso-ethics@uow.edu.au.

FREEDOM OF CONSENT

Participation in this project and consent to the use of data collected for publication is entirely voluntary. You are free to deny consent before, or during data collection. In the latter case, such withdrawal of consent will be performed at the time you specify, and not at the end of a particular trial. If you do withdraw, the researchers will discard your data. However, your participation, or withdrawal of consent, will not influence your present or future involvement with the St George Illawarra Dragons Rugby League Football Club or the University of Wollongong. In the case of student involvement, such participation or withdrawal of consent will not influence grades awarded by the University. You have the right to withdraw from any experiment, and this right shall be preserved over and above the goals of the experiment.

CONFIDENTIALITY AND OWNERSHIP OF DATA

All questions, answers and results from this study will be treated with absolute confidentiality. Participants will not be identified within reports or manuscripts using either their names or initials. Instead, subjects will only be identified via alphanumeric codes. Occasionally, we will record parts of experiments using video or still photographs. These images may be used for conference presentations, dissertations, manuscripts, lectures or laboratory demonstrations. Prior to any such photography, you will be asked if you would like to provide consent for such images to be captured, and there is a question concerning this on the Informed Consent form. However, there is no obligation to provide this consent.

APPENDIX THREE: INFORMED CONSENT FORM

INFORMED CONSENT FORM:

AN OBJECTIVE ANALYSIS OF DATA ACQUISITION SYSTEMS USED IN PROFESSIONAL SPORT TO PREDICT INJURY AND PERFORMANCE

I confirm receipt of the subject information package and informed consent form.

I understand that consent is given for data collection and interpretation under the conditions of my employment with St. George Illawarra Dragons Rugby League Football Club.

Name:

Signed:

Date:

However, it is not a requirement of my employment to consent to the use of data for publication purposes as such I ……………………………………………….. choose NOT to provide my consent for data collected from my person in any research related publication.

Signed …………………………………………………………..

Date ………………………………………………………………

Witness ………………………………………………………....

Date ………………………………………………………………

APPENDIX FOUR: ETHICS APPROVAL

UNIVERSITY OF WOLLONGONG

RENEWAL & AMENDMENTS APPROVAL
In reply please quote: HE12/421
Further Enquiries Phone: 4221 3386

4 December 2013

Dr John Sampson
School of Health Science
University of Wollongong

Dear Dr Sampson,

Thank you for submitting the progress report. I am pleased to advise that **renewal and amendments** received 2 December 2013 to the following Human Research Ethics application have been **approved**.

Ethics Number:	HE12/421
Project Title:	An objective analysis of data acquisition systems used in professional sport to predict injury and performance
Researchers:	Dr John Sampson, Mr Andrew Gray, A/Professor Peter Caputi, Mr John Davey, Mr Billy Hulin
Date Approved:	3 December 2013
Amendment/s:	Additional Researcher: Mr Billy Hulin
Renewed From:	18 December 2013
New Expiry Date:	17 December 2014

Please note that approvals are granted for a twelve month period. Further extension will be considered on receipt of a progress report prior to expiry date.

This certificate relates to the research protocol submitted in your original application and all approved amendments to date. Please remember that in addition to completing an annual report the Human Research Ethics Committee also requires that researchers immediately report:

- proposed changes to the protocol including changes to investigators involved
- serious or unexpected adverse effects on participants
- unforseen events that might affect continued ethical acceptability of the project.

Yours sincerely,

Professor Jim Greenstein
Chair, UOW & ISLHD Health and Medical
Human Research Ethics Committee

Ethics Unit, Research Services Office
University of Wollongong NSW 2522 Australia
Telephone (02) 4221 3386 Facsimile (02) 4221 4338
Email: rso-ethics@uow.edu.au Web: www.uow.edu.au

APPENDIX FIVE: RESEARCHER DECLARATION

RESEARCHER DECLARATION

Ethics Number: HE12/421

Project Title: An objective analysis of data acquisition systems used in professional sport to predict injury and performance

Researchers: Dr John Sampson, Mr Andrew Gray, Assoc. Prof. Peter Caputi, Mr John Davey

I confirm that I have read the protocol and ethics application for the above project, including the declaration for researchers, and that I understand and accept the responsibilities as described.

Name: Mr Billy Hulin

Role in project: Masters research student

Qualifications/relevant experience: Bachelor of Exercise and Sport Science

Signature:

Date: 21/11/2013