The Combined Effect of Training and Match Loads on Injury Risk in Professional Australian Footballers

Nicholas B. Murray

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The combined effect of training and match loads on injury risk in professional Australian Footballers

Nicholas B. Murray

SCHOOL OF EXERCISE SCIENCE
AUSTRALIAN CATHOLIC UNIVERSITY
McAuley Campus
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This thesis is submitted in accordance with the requirements of The Graduate Research Office, Australian Catholic University for the degree of Doctor of Philosophy by Nicholas B. Murray.
Declaration

This thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for or been awarded another degree or diploma. No parts of this thesis have been submitted towards the award of any other degree or diploma in any other tertiary institution. No other person’s work has been used without due acknowledgement in the main text of the thesis. All research procedures reported in the thesis received the approval of the relevant Ethics/Safety Committees (where required).

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Published Works by the Author Incorporated into the Thesis

The studies outlined below were conducted during this PhD and make up the presented thesis; each paper has been published following peer review.


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Submitted for publication to Br J Sports Med.

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I hereby declare that my contribution to each of the six published/submitted manuscripts, as outlined above, to be accurate and true.

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Abstract

Australian football is a dynamic team sport, which requires players to perform a large number of high-intensity efforts, combined with low-intensity activities throughout a match. Due to the complex and unique demands of the sport, players require an adequate training stimulus to develop and enhance the physical qualities required to succeed at the highest level. The ability to develop physically challenging but appropriate training at an individual level to 1) enhance the technical and physical qualities required, and 2) minimise the negative response to training (i.e. injury, illness, etc.) is a crucial task for practitioners involved in the preparation of elite players.

The cost of injury in elite sport is substantial, with player availability seen as a key factor in the success or failure of any professional sporting organisation. It is typically suggested that teams with higher injury rates are more likely to be negatively impacted through poor team performance, compared with teams with lower injury rates. If injuries (particularly non-contact, soft-tissue injuries) can be considered ‘largely’ avoidable, then the role of workload becomes a key component in any sporting organisation to manage and minimise the risk of injury.

The notion that workload and injury are interrelated is well established, yet the cost of injury remains significant at the professional level of Australian football. The overall aim of this program of research was to use scientific literature to understand the relationship between workload, injury, and performance in elite Australian football players and then improve the understanding of workload management and modelling of workload variables measured using
a commercially available microtechnology unit. The program of research in this thesis first produced a comprehensive literature review to identify the current problem(s). The six subsequent chapters of original research built on the literature review to examine, in elite Australian football, (1) a previously suggested fitness-fatigue model on injury risk, (2) the importance of pre-season training on in-season availability, (3) the use of relative speed zones to model workload at an individual level, (4) a newly proposed fitness-fatigue model, (5) the differences between fitness-fatigue models in an applied setting, and finally (6) the application of a training monitoring system on injury rates.

A previously-established monitoring tool, the acute:chronic workload ratio, was used to quantify the relationship between workload and injury in a cohort of professional Australian football players. The size of the acute workload in relation to the size of the chronic workload was calculated as an acute:chronic workload ratio. A very high acute:chronic workload ratio (i.e. > 2.0) for total distance was associated with a 5 to 8-fold increase in injury risk during the season. Similarly, players with a high-speed running acute:chronic workload ratio of > 2.0 were 5-11 times more likely to sustain an injury in both the current and subsequent week. These findings demonstrate that sharp increases in acute workload significantly increase the likelihood of injury in both the current and subsequent week.

Once this relationship was confirmed in this cohort, the second study explored the effect of the amount of pre-season training completed on injury risk during the in-season period. Players who completed greater amounts of pre-season training (> 50% sessions completed) maintained higher workloads throughout the competitive phase of the season, as well as competed in a greater number of competitive matches. Further, injury rates were ~2 times
greater in a low training load group (< 50% sessions completed), when compared with a high training load group (> 85% sessions completed). These findings demonstrate that completing a greater proportion of pre-season training resulted in higher training loads and greater participation in training and competition during the subsequent competitive season.

In study 3, a new method of workload and injury modelling was investigated and compared to a previous model. Specifically, the newly proposed model utilised an exponentially weighted moving average to calculate the acute:chronic workload ratio, as opposed to the previously used rolling averages method. There were significant differences in the acute:chronic workload ratio values for moderate, high, and very high ranges. Although both models demonstrated significant associations between a very high acute:chronic workload ratio (i.e. > 2.0) and increased injury likelihood, the exponentially weighted moving averages model was more sensitive for detecting this increased risk. These findings demonstrate that (1) large spikes in workload are associated with increased injury risk, irrespective of model used, and (2) the exponentially weighted moving averages model is more sensitive in detecting increased injury risk with high acute:chronic workload ratios.

The fourth study investigated the use of absolute and relative speed zones to quantify workload and the subsequent risk of injury. Players were divided into three groups based on maximum velocity; (1) faster, (2) moderate, or (3) slower, with individual workloads analysed using a pre-defined absolute speed threshold, or a relative individualised speed threshold. The differences in workload were calculated, along with differences in injury likelihood using both the rolling average and exponentially weighted moving average methods of workload calculation. Faster players demonstrated a significant over-estimation of very high-speed
running when absolute thresholds were applied, while slower players demonstrated a significant underestimation of high- and very high-speed running when compared to their relative thresholds. These findings demonstrate that the use of relative thresholds significantly alters the amount of very high-speed running performed and should be considered in the prescription of workload.

Chapter 7 provides a case series of the differences in loading patterns between the rolling averages and exponentially weighted moving averages models of acute:chronic workload ratio to assess how large ‘spikes’ in workload can occur in one or both of the models. While both models are associated with increased injury risk, it is still unclear how these models differ at an individual workload level. This study explored three professional Australian football player’s loading patterns coupled with the proportion of similarities and differences found between the two existing workload model calculations, along with management strategies for different players in different phases of training.

Finally, the application of a training monitoring system to reduce injury rates was investigated in a cohort of professional Australian football players. The relationship between the acute:chronic workload ratio and injury was established over three seasons (2014-2016). In the final season (2017) of the study, an attempt was made to minimise the number of spikes in workload a player experienced. A significant reduction in workload spikes was observed over the entire 2017 season. In addition, a significant reduction in injury rate occurred. These findings demonstrated that the use of a training monitoring system decreased the number of workload spikes a player encountered, subsequently reducing the incidence of non-contact soft-tissue injury.
Collectively, this thesis has highlighted the positive and negative effects of workload in relation to injury, and more specifically how workload is related to injury risk in elite Australian footballers. This applied research advances our understanding of workload and injury, and contributes to the body of literature on injury risk in elite Australian footballers.
Table of Contents

Declaration......................................................................................................................ii

Published Works by the Author Incorporated into the Thesis........................................ iii

Acknowledgements................................................................................................iv

Abstract..................................................................................................................ix

Table of Contents..................................................................................................1

List of Tables .......................................................................................................8

List of Figures .......................................................................................................10

List of Abbreviations............................................................................................13

General Introduction ............................................................................................15

  1.1 Aims of the Current Research ...........................................................................17

Literature Review..................................................................................................19

  2.1 Overview of Australian Football.......................................................................20

  2.2 Match Demands...............................................................................................20

  2.3 Workload Monitoring......................................................................................21

  2.4 Response to Workloads....................................................................................24

  2.5 Injury.................................................................................................................25

  2.6 The Workload-Injury Relationship .................................................................26

    2.6.1 Individual Sports......................................................................................27

    2.6.2 Team Sports.............................................................................................27

    2.6.3 Australian Football..................................................................................42

    2.6.4 The Acute:Chronic Workload Ratio.........................................................45

  2.7 Specific Aims of the Current Research............................................................51

Nick Murray  
Load and Injury in AFL
Study 1 – Individual and combined effects of acute and chronic running loads on injury risk in elite Australian footballers

3.1 Abstract

3.2 Introduction

3.3 Methods

3.3.1 Participants

3.3.2 Training and Competition Loads

3.3.3 Calculating the Acute:Chronic Workload Ratio

3.3.4 Statistical Analysis

3.4 Results

3.4.1 Current Week

3.4.2 Subsequent Week

3.5 Discussion

3.5.1 Limitations

3.6 Conclusion

3.7 Acknowledgements

Study 2 – Relationship between pre-season training load and in-season availability in elite Australian Football players

4.1 Abstract

4.2 Introduction

4.3 Methods

4.3.1 Participants

4.3.2 Training and Competition Loads

4.3.3 Statistical Analysis

Nick Murray

Load and Injury in AFL
Study 3 – Calculating acute:chronic workload ratios using exponentially weighted moving averages provides a more sensitive indicator of injury likelihood than rolling averages.... 93

5.1 Abstract ......................................................................................................................... 94
5.2 Introduction .................................................................................................................... 95
5.3 Methods ......................................................................................................................... 97
  5.3.1 Participants ................................................................................................................. 97
  5.3.2 Quantifying Workloads ............................................................................................. 97
  5.3.3 Definition of Injury .................................................................................................. 98
  5.3.4 Acute:Chronic Workload Ratio Calculation .............................................................. 98
    5.3.4.1 Rolling Averages Acute:Chronic Workload Ratio .............................................. 98
    5.3.4.2 Exponentially Weighted Moving Averages Acute:Chronic Workload Ratio ..... 99
  5.3.5 Statistical Analysis .................................................................................................. 100
5.4 Results .......................................................................................................................... 100
  5.4.1 Injuries ..................................................................................................................... 100
  5.4.2 Different Methods of ACWR Calculation ................................................................. 101
  5.4.3 Injury Likelihoods for each ACWR Model ................................................................. 103
    5.4.3.1 Pre-Season ............................................................................................................ 103
    5.4.3.2 In-Season ............................................................................................................. 105
  5.4.4 Between-Model Comparisons .................................................................................. 107
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>Abstract</td>
<td>141</td>
</tr>
<tr>
<td>7.2</td>
<td>Introduction</td>
<td>142</td>
</tr>
<tr>
<td>7.2.1</td>
<td>The Role of Workload in the Decision-Making Process</td>
<td>142</td>
</tr>
<tr>
<td>7.2.2</td>
<td>The Role of the Acute:Chronic Workload Ratio in Injury Prevention</td>
<td>142</td>
</tr>
<tr>
<td>7.3</td>
<td>A Player Returning from Injury</td>
<td>145</td>
</tr>
<tr>
<td>7.4</td>
<td>A Player Who Plays Regularly, But Doesn’t Train Consistently</td>
<td>145</td>
</tr>
<tr>
<td>7.5</td>
<td>A Player with a Consistent Playing and Training Schedule</td>
<td>147</td>
</tr>
<tr>
<td>7.6</td>
<td>Practical Applications</td>
<td>149</td>
</tr>
<tr>
<td>7.7</td>
<td>Conclusions</td>
<td>149</td>
</tr>
</tbody>
</table>

Study 6 – Reducing spikes in workload and building chronic workload decreases injury rate and burden in elite Australian football players | 153 |
<p>| 8.1     | Abstract | 154 |
| 8.2     | Introduction | 156 |
| 8.3     | Methods | 158 |
| 8.3.1   | Participants | 158 |
| 8.3.2   | Quantifying Workloads | 159 |
| 8.3.3   | Definition of Injury | 159 |
| 8.3.4   | Acute:Chronic Workload Ratio Calculation | 159 |
| 8.3.5   | Testing the Acute:Chronic Workload Ratio Model | 160 |
| 8.3.6   | Statistical Analysis | 162 |
| 8.3.6.1 | Spikes in workload | 162 |
| 8.3.6.2 | Workload and injury | 162 |
| 8.3.6.3 | Wellness | 163 |
| 8.3.6.4 | Injury rates | 163 |</p>
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.4 Results</td>
<td>163</td>
</tr>
<tr>
<td>8.4.1 Differences in chronic workloads</td>
<td>163</td>
</tr>
<tr>
<td>8.4.1.1 Pre-Season</td>
<td>163</td>
</tr>
<tr>
<td>8.4.1.2 In-Season</td>
<td>165</td>
</tr>
<tr>
<td>8.4.1.3 Entire Season</td>
<td>167</td>
</tr>
<tr>
<td>8.4.2 Wellness</td>
<td>169</td>
</tr>
<tr>
<td>8.4.3 Spikes in workload</td>
<td>170</td>
</tr>
<tr>
<td>8.4.3.1 Pre-Season</td>
<td>170</td>
</tr>
<tr>
<td>8.4.3.2 In-Season</td>
<td>172</td>
</tr>
<tr>
<td>8.4.3.3 Entire Season</td>
<td>172</td>
</tr>
<tr>
<td>8.4.4 Injury Rates and Burden</td>
<td>173</td>
</tr>
<tr>
<td>8.5 Discussion</td>
<td>175</td>
</tr>
<tr>
<td>8.6 Conclusions</td>
<td>179</td>
</tr>
<tr>
<td>8.7 What are the New Findings?</td>
<td>180</td>
</tr>
<tr>
<td>8.8 How Might this Impact on Clinical Practice in the Near Future?</td>
<td>180</td>
</tr>
<tr>
<td>8.9 Acknowledgements</td>
<td>180</td>
</tr>
<tr>
<td>Summary and Conclusions</td>
<td>181</td>
</tr>
<tr>
<td>9.1 Overview</td>
<td>182</td>
</tr>
<tr>
<td>9.2 Summary of Major Findings</td>
<td>182</td>
</tr>
<tr>
<td>9.3 Points of Difference</td>
<td>192</td>
</tr>
<tr>
<td>9.4 Strengths</td>
<td>193</td>
</tr>
<tr>
<td>9.5 Limitations</td>
<td>194</td>
</tr>
<tr>
<td>9.6 Future Directions</td>
<td>195</td>
</tr>
<tr>
<td>9.7 Practical Applications</td>
<td>196</td>
</tr>
</tbody>
</table>
9.8 Conclusions ........................................................................................................... 197
References.................................................................................................................... 199
Appendices.................................................................................................................. 217
Appendix A – Evidence of Publications ........................................................................ 218
Appendix B – Information Letters and Consent Forms .................................................. 222
Chapters 3, 5, 7, & 8 .................................................................................................... 222
Chapter 6 .................................................................................................................... 230
Ethics Approval .......................................................................................................... 234
Appendix C – Approval ID: 2015-50E ........................................................................ 234
Appendix D – Approval ID: 2015-182E ...................................................................... 235
Appendix E – Approval ID: 2016-40E ...................................................................... 236
List of Tables

Table 1. Summary of studies investigating the relationship between workload and injury.

Table 2. Descriptive statistics for all participants’ external workload variables over the course of the study.

Table 3. Quantification of weekly training and game loads throughout the pre- and in-season period for each load group (i.e. high, medium, and low).

Table 4. Relationships among the percentage of pre-season completed, match availability, pre-season training load, and in-season training load.

Table 5. Variance ($R^2$) in injury explained by the rolling daily averages and exponentially weighted moving averages ACWR models.

Table 6. Weekly descriptive statistics for all participants’ external workload variables, both absolute and relative, over the duration of the study.

Table 7. Description of differing acute and chronic workload values using the rolling averages and exponentially weighted moving averages models.

Table 8. Strengths and weakness of the rolling averages and exponentially weighted moving averages models.

Table 9. Calculations for acute and chronic workloads, along with the acute:chronic workload ratio using rolling averages and exponentially weighted moving averages for a selected time period for case series example C.

Table 10. Average number of workload spikes (i.e. ACWR > 1.5) per player per season during both the pre-season and in-season periods calculated using the exponentially weighted moving averages ACWR model.
Table 11. Summary of study aims, experimental hypotheses, and findings.
List of Figures

Figure 1. Likelihood of injury at acute (A) and chronic (B) external workloads, and acute:chronic workload ratio [ACWR] (C) for the current week, and acute (D) and chronic (E) external workloads, and acute:chronic workload ratio [ACWR] (F) for the subsequent week, during the pre-season period.

Figure 2. Likelihood of injury at acute (A) and chronic (B) external workloads, and acute:chronic workload ratio [ACWR] (C) for the current week, and acute (D) and chronic (E) external workloads, and acute:chronic workload ratio [ACWR] (F) for the subsequent week, during the in-season period.

Figure 3. Total duration of training hours during the pre- (A) and in-season (C) periods, with proportion of sessions completed for each load group (i.e. high, medium, and low) during the pre- (B), and in-season (D) period.

Figure 4. Quantification of weekly training and game loads (i.e. total loads) throughout the first and second half of the in-season period for each load group (i.e. high, medium, and low).

Figure 5. The acute:chronic workload ratio (ACWR) modelled using each method: rolling averages and exponentially weighted moving averages.

Figure 6. Likelihood of injury at each acute:chronic workload ratio range during the pre-season period for the current day for (a) total distance, (b) moderate-speed distance, (c) high-speed distance, and (d) player load.

Figure 7. Likelihood of injury at each acute:chronic workload ratio range during the in-season period for the current day for (a) total distance, (b) moderate-speed distance, (c) high-speed distance, and (d) player load.
Figure 8. Absolute and relative average weekly workloads of faster (a, b, c, d) and slower (I, j, k, l) players across the duration of the pre- and in-season periods.

Figure 9. Likelihood of injury at differing acute workload ranges for faster (low-speed, A; moderate-speed, B; high-speed, C; very high-speed, D) and slower (low-speed, E; moderate-speed, F; high-speed, G; very high-speed, H) players.

Figure 10. Likelihood of injury at differing chronic workload ranges for faster (low-speed, A; moderate-speed, B; high-speed, C; very high-speed, D) and slower (low-speed, E; moderate-speed, F; high-speed, G; very high-speed, H) players.

Figure 11. Likelihood of injury at differing acute:chronic workload ratio ranges for faster (low-speed, A; moderate-speed, B; high-speed, C; very high-speed, D) and slower (low-speed, E; moderate-speed, F; high-speed, G; very high-speed, H) players.

Figure 12. Daily workloads, along with acute and chronic total distance, and two models of ACWR calculation (RA & EWMA) of three individual players over a 28-day period. Daily load = the total distance completed on a given day. Acute load = rolling 7-day average. Chronic load = 28-day rolling average. RA ACWR = acute:chronic workload ratio using the rolling averages model. EWMA ACWR = acute:chronic workload ratio using the exponentially weighted moving averages model. * represent spikes (i.e. ACWR > 1.5) in EWMA ACWR.

Figure 13. Average chronic workloads for total distance, high-speed distance, very high-speed distance, and Player Load™ over four consecutive pre-season periods. * denotes significantly different (p<0.05) from the 2017 season.

Figure 14. Average chronic workloads for total distance, high-speed distance, very high-speed distance, and Player Load™ over four consecutive in-season periods. * denotes significantly different (p<0.05) from the 2017 season.
**Figure 15.** Average chronic workloads for total distance, high-speed distance, very high-speed distance, and Player Load™ over four consecutive entire season periods. * denotes significantly different (p<0.05) from the 2017 season.

**Figure 16.** Average wellness data over four consecutive seasons for the day of when the workload completed resulted in an ACWR value of either > 1.5 or < 1.5.

**Figure 17.** Injury rates and injury burden, expressed per 1,000 exposure hours, across the duration of the four years for (A) pre-season, (B) in-season, and (C) the whole season. * denotes significantly different (p<0.05) from the previous seasons.

**Figure 18.** A heat map displaying the injury rates for each combination of chronic workload and ACWR across the duration of the four years. Each row represents a season, while each column represents a different workload variable.

**Figure 19.** A schematic diagram displaying the relationship between acute and chronic workload, the ACWR, player availability, and injury risk in professional Australian football.
**List of Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACWR</td>
<td>Acute:chronic workload ratio</td>
</tr>
<tr>
<td>AF</td>
<td>Australian football</td>
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<tr>
<td>AFL</td>
<td>Australian Football League</td>
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<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
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<tr>
<td>au</td>
<td>Arbitrary units</td>
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<tr>
<td>CI</td>
<td>Confidence interval</td>
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<tr>
<td>CV</td>
<td>Coefficient of variation</td>
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<td>cm</td>
<td>Centimetre</td>
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<tr>
<td>ES</td>
<td>Effect size</td>
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<tr>
<td>EWMA</td>
<td>Exponentially weighted moving averages</td>
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<tr>
<td>GPS</td>
<td>Global positioning system</td>
</tr>
<tr>
<td>HTL</td>
<td>High training load group</td>
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<tr>
<td>kg</td>
<td>Kilogram</td>
</tr>
<tr>
<td>km.hr(^{-1})</td>
<td>Kilometers per hour</td>
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<tr>
<td>LTL</td>
<td>Low training load group</td>
</tr>
<tr>
<td>MTL</td>
<td>Medium training load group</td>
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<tr>
<td>m.min(^{-1})</td>
<td>Meters per minute</td>
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<tr>
<td>OR</td>
<td>Odds ratio</td>
</tr>
<tr>
<td>r</td>
<td>Correlation</td>
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<tr>
<td>R(^2)</td>
<td>R-squared</td>
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<tr>
<td>RA</td>
<td>Rolling averages</td>
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<tr>
<td>RPE</td>
<td>Rate of perceived exertion</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>RR</td>
<td>Relative risk</td>
</tr>
<tr>
<td>SD</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>SWC</td>
<td>Smallest worthwhile change</td>
</tr>
<tr>
<td>TEM</td>
<td>Typical error of measurement</td>
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<tr>
<td>$\chi^2$</td>
<td>Chi squared</td>
</tr>
</tbody>
</table>
Chapter 1

General Introduction
The ability of players to maintain the required level of physical activity throughout a match is vital to the success or demise of a football team. With the increased physical demands of Australian football (AF) [1], a higher injury incidence has also been observed [2-7]. Despite this, the relationship between training and competition workloads and subsequent injury risk is unclear. Therefore, it is important to explore this relationship within elite Australian football. Gabbett [8] clearly states that the challenge for strength and conditioning and sport science staff is to provide an adequate training stimulus – enough to achieve the physical qualities required to succeed at an elite level of competition (i.e. the benefit), without increasing the subsequent risk of injury (i.e. the cost). While we now know that both under-and over-training can increase the risk of injury [8-10], further work is required to better understand the relationship between training workloads and injuries, how individuals within a team respond to the same given workload, and the optimum training workload for each player – the “… ideal cost-benefit ratio” (p.2) [8].

The fitness-fatigue model, where performance represents the difference between fitness and fatigue, aims to predict performance by comparing acute and chronic workloads [11-14]. The fitness after-effect results in a positive physiological response and in turn improved performance, whereas the fatigue after-effect results in a negative physiological response and a subsequent increase in injury risk [9, 11-13, 15]. The difference between the positive physiological response and the negative physiological response provides either a low or high acute:chronic workload ratio [9, 14]. Initial workload-injury research has begun to show a clear link between workload and injury risk [14, 16, 17], however further extensive work is required.
Injuries are common in elite sport, with player availability seen as a key factor in the success or failure of a professional team [18, 19]. Contact injuries are thought to be ‘largely’ unavoidable, while non-contact soft-tissue injuries are thought to be ‘largely’ preventable and associated with errors in training load, either too high or too low [20-22]. If true, sports science, medical, and coaching staff hold an important role in managing and minimising the risk of injury for players in their respective team [19, 23]. Recent research has explored the relationship between training workloads and injury risk in Australian football [24, 25]. While these studies compared injury risk with absolute cumulative workload (e.g. 1-week, or 3-week), or previous-to-current week changes in workload, to date, no research has investigated the comparison of the current workload relative to the previous short-to-medium term workload, and the ratio of the acute and chronic workload (i.e. the acute:chronic workload ratio) and subsequent injury risk in Australian football.

The nature of injury is largely multi-factorial [26], with many factors contributing to whether a player sustains a non-contact soft-tissue injury on any given day. First, a framework for quantifying sport-specific injury risk should be completed to identify if there is a relationship between workload and injury risk in Australian football. Secondly, consideration should be given to factors which may influence this workload-injury relationship including but not limited to; chronic workload [16, 17, 27], amount of pre-season training complete [15], and different methods of workload quantification. Finally, the influence of practitioner intervention should be examined to identify whether the rate of non-contact soft-tissue injuries can be reduced in professional sport. With these in mind, it is clear that it is important to further investigate and identify the dynamic relationship between workload and injury in Australian football.

**1.1 Aims of the Current Research**

Nick Murray  
*Load and Injury in AFL*
The overall aim of this thesis was to investigate the relationship between workload and injury in elite Australian football players. Furthermore, we sought to identify and consolidate new methods to quantify both absolute and relative workload and the subsequent effect on injury risk. This research provides a greater understanding of the relationship between workloads and injury in Australian football players. It examined the effect of acute and chronic running workloads, the acute:chronic workload ratio, high and low training workloads, relative workloads, and subsequent injury risk. Results from this research will provide coaching staff, strength and conditioning staff, and sport scientists with a greater understanding of the relationship between workload and injury, to enhance the individualised training, recovery, and rehabilitation of elite Australian football players.
Chapter 2

Literature Review
2.1 Overview of Australian Football

Australian football (AF) is an intermittent team sport played by junior and senior players nationally at elite, sub-elite, and amateur levels. Two teams of eighteen players (plus four interchange players) compete in a match lasting 100 + minutes, comprising four quarters of 20-30 minutes in duration, separated by a 6-minute and 20-minute rest interval between quarters and halves, respectively [28]. Each team of eighteen players is comprised of eight different positions [29]. Players can be divided into four sub-groups according to their position; these include forwards (half-forward, centre half forward, full forward), midfielders, defenders (half back, centre half back, fullback), and ruckmen [29].

2.2 Match Demands

Players are required to perform multiple accelerations and physical contacts throughout a match, interspersed with high- (i.e. sprinting, running) and low-speed (i.e. jogging, walking, standing) movements [1, 28-31]. It is the combination of physical contacts, and volume of low-speed and high-speed running, which make the physical demands of AF unique. The ability to quantify the demands of competition is vital to develop specific training programs to effectively prepare athletes to meet these demands. The physical demands of competition are well-known, with multiple studies quantifying these demands using Global Positioning System (GPS) analysis [1, 28-32].

Depending on position, players from the elite Australian Football League (AFL) typically cover between 11.5–13.0 km over the course of a game [1, 28, 29, 31]. Midfielders and half forwards/backs cover the largest distance over the duration of a game, covering 12.6 km and 12.9 km, respectively [29]. Key position players (i.e. full-forward and full-back) cover
slightly less distance (~11.1–12.0 km) [1, 29], followed by ruckmen (~10.8 km) [29]. Despite the differences in total distance, the relative distances covered are largely the same between positional groups, with elite AF players typically covering ~120–135 m.min\(^{-1}\) [29]. In addition to informing practitioners about total running volumes, GPS analysis has also provided information on the proportion of high-intensity running and high-intensity efforts (i.e. sustained high-speed running for a minimum of 2 seconds) that players perform during competition. Coutts and associates [31] reported that elite AF players complete 28.6 ± 8.1 sprint (i.e. above 23 km.hr\(^{-1}\)) efforts in a match, along with 3,880 m of high speed running (>20 km.hr\(^{-1}\)) in a match at an intensity of 40.1 m.min\(^{-1}\) [31]. In more recent work, the use of an ‘integrated’ approach whereby match demands are contextualised by assimilating physical and technical data simultaneously has been proposed [33]. While this approach requires further work before regular adoption, this concept may aid in the understanding of the influence of technical and tactical actions on physical performance during intermittent team sport match play.

Physical contacts (i.e. tackles, bumps, and shepherds) are also a regular occurrence in Australian football, although noticeably less than other contact team sports when considered relative to match time [34]. Tackling is considered an important part of Australian football, with players completing on average 3.9 tackles per game [35]. While tackling is likely to be less forceful and frequent than other contact sports, tackles in AF consist of moderate impact forces and movement velocities, which add to the total load experienced by players [35].

2.3 Workload Monitoring
GPS is a modern technology that allows the three-dimensional tracking of movement in both air- and land-based environments [36]. Multiple studies have validated the use of GPS technology for monitoring of speed, acceleration, and velocity across a wide range of human locomotion velocities [37-41]. The increased commercial availability and use of GPS technology in team sports has allowed researchers and sport scientists to objectively quantify movement demands of their particular sport. The use of GPS technology in published literature has been extensive, particularly in Australian football [1, 28-32, 35, 42, 43], rugby union [44-48], rugby league [49-53], soccer [54-57], cricket [58-60], and hockey [61-63].

Studies that have objectively described the competition demands of AF using GPS [1, 28-32, 35, 42, 43, 64] have enhanced the knowledge and understanding of the physical demands of the game. While these advancements are important, there are issues surrounding the quantification of these demands. First, the reliability and validity of the GPS devices to measure short, high-intensity activities have been previously questioned – although as the sampling frequency has increased with advancements in wearable technology, so too has the measurement accuracy [65]. Secondly, with several types of commercially available microtechnology units on the market, comparison between studies using differing units becomes difficult and may explain some of the discrepancy seen [38].

Coupled with inertial measurement sensors, these microtechnology units have become an invaluable method of accurately monitoring athlete workloads. Located within the Optimeye GPS Units (Catapult Innovations, Melbourne, Australia) is a 100 Hz tri-axial accelerometer, which is a highly receptive inertial measurement sensor, used to measure the frequency and magnitude of movement in three dimensions; anterior-posterior, medial-lateral, and
longitudinal [66]. Boyd and colleagues [67] found that the accelerometers offered an acceptable measure of within-unit (Dynamic: Coefficient of variation [CV] 0.91 to 1.05%; Static: CV 1.10%) and between-unit (Dynamic: CV 1.02 to 1.04%; Static: CV 1.10%) reliability [67]. In further work, the intra-device reliability has been shown to be excellent displaying the within device CV to be less than 2% [68]. Moreover, the use of an algorithm using accelerometer, gyroscope, and magnetometer technology located within the MinimaxX GPS units have been validated to quantify the contact load experienced by athletes in collision sports [69], although this technology has not been validated for use in Australian football [70].

Published literature surrounding the use of GPS technology to quantify match demands across a range of sports is widespread [1, 28-32, 42, 48, 50, 51, 53, 61-63, 65], however to date, a common limitation of these studies is a failure to account for differences in the individual capacities of players. That is, faster players may work at a relatively lower percentage of their maximum speed, while slower players may work at a relatively higher percentage [71]. It has been shown that absolute velocity thresholds may underestimate the quantity of high-intensity running performed during professional soccer competition [72]. Similarly, during women’s rugby sevens competition, it has been shown that the use of a standardised velocity threshold underestimated the amount of high-intensity running by up to 30% [73]. Further, the individualisation of these velocity bands has been shown to increase the amount of high-intensity running of relatively slower athletes, while subsequently decreasing the amount of high-intensity running performed by relatively faster athletes [71, 74]. Thus, it is suggested that the use of individualised velocity thresholds has the potential to improve the individual quantification of game demands, and aid in the prescription,
implementation, and effectiveness of training programs and recovery sessions [71, 73, 75, 76].

2.4 Response to Workloads

Originally proposed by Banister [11, 12], the fitness-fatigue model states that the training stress placed on an athlete results in two contrasting responses – fitness and fatigue. Performance represents the difference between a positive function (i.e. fitness) and a negative function (i.e. fatigue), where chronic workload represents fitness and acute workload represents fatigue [9]. The fitness after-effect results in a positive physiological response and in turn improved performance, whereas the fatigue after-effect results in a negative physiological response and a subsequent increase in injury risk [11-13]. The difference between the positive physiological response and the negative physiological response provides either a low or high acute:chronic workload ratio, respectively [9, 14, 16, 17]. For example an acute workload of 10,000 m, and a chronic workload of 15,000 m would result in an acute:chronic workload ratio of 0.67 (i.e. 10,000 m / 15,000 m). It is suggested that the highest level of performance occurs when the negative physiological response (i.e. fatigue) is minimal, and the positive physiological response (i.e. fitness) is maximal [13]. With the apparent association between fitness and fatigue [11-13, 77], and a high acute:chronic workload ratio and injury [9, 14, 16, 17], individualised monitoring of athlete’s workloads is crucial. For optimal performance, it is essential to understand acute and chronic workloads, and the acute:chronic workload ratio in order to adequately prescribe and administer both training workloads, and periods of recovery.

Given the physical demands of competition, players experience both immediate and delayed fatigue for a number of days following competition [78-80]. This fatigue can be measured as
(1) transient reductions in exercise intensity [81], (2) decreases in both low- and high-speed running [1, 30-32] during competition, and (3) increases in neuromuscular fatigue, measured through decreases in countermovement jump performance [82], and increases in blood creatine kinase levels [82], in the days following competition. It is well established that high-speed running is vital to success in team sports [81], however high-speed activities during competition are coupled with increased fatigue during a match [83, 84]. Previous work has found that high-intensity running is significantly decreased from the first half to the second half in top level soccer [84, 85]. Similarly, high-intensity running of elite Australian football players has been shown to decrease during the latter stages of competition [30]. Given the proposed significance of high-speed running to performance [81], it is important to quantify high-speed running for individual players, relative to their physical capacity [71-73, 75, 76].

### 2.5 Injury

In 1992, the Australian Football League (AFL) implemented a competition-wide injury surveillance project called ‘The AFL Injury Report’. These results are quantified in a report that examines injury incidence and attempts to identify developing injury trends [2-7, 86]. Over the previous two decades, injuries to the hamstrings, knee anterior cruciate ligament, and groin were the most common, with hamstring strains the most prevalent at a rate of six hamstring strains per club per season [3, 6, 86]. Recent findings suggest that the incidence of hamstring and groin injuries have decreased during 2011-2013 compared with 2008-2010, coupled with a significant increase in calf strains and knee tendon injuries, and a number of other lower limb injuries [4]. Further, a higher injury incidence and prevalence in first-year players has been found [87, 88], suggesting that they may not be as capable of tolerating training workload as older players who have been exposed to multiple years of training in a professional sporting environment [89, 90]. However, Rogalski et al. [25] found that players
with both 2–3 (OR [Odds Ratio]=0.22) and 4–6 (OR=0.28) years of playing experience had a significantly lower risk of injury than players with 7+ years of playing experience, suggesting that age may also be a factor in injury risk. Greater knowledge on injury prevention, injury incidence, and injury rehabilitation may influence the lower injury incidence reported [3, 6].

Although the annual public release of injury surveillance data by the AFL is novel, this report fails to examine the relationship between workloads and the subsequent incidence of injury [4, 5]. The importance of acknowledging that training and competition workloads are strongly associated with injury incidence has been proposed in an updated injury aetiology model [26]. In this model, internal risk factors are differentiated into both modifiable and non-modifiable factors, while workloads contribute to injury in three ways; (1) exposure to external risk factors and potential inciting events, (2) fatigue, or negative physiological effects, and (3) fitness, or positive physiological adaptations [26]. Given the importance of player management [91] and physical performance [1, 30, 31] to sporting success, it is important to not only consider common trends in injury surveillance, but also actively monitor and explore the relationship between training and competition workloads and injury.

2.6 The Workload-Injury Relationship

In professional sport, an increased emphasis has been placed upon quantifying workloads and the relationship between workload and injury. Gamble [91] suggests “… controlling player’s competition workloads and exposure to the stresses and conditions of fatigue involved in match-play will reduce their risk of injury” (p.36). Moreover, the “… rationale for restricting the player’s overall workload is to limit training-related stresses and residual fatigue, thereby reducing the number of injuries sustained in both training and competition” (p.36). Further, it
is suggested that player’s should not be exposed to workloads greater than what they are prepared to perform, as this will increase their risk of injury [9]. However, workload is vital to enhance the physical qualities required to succeed at the highest level of any particular sport, so it is crucial to understand how workload affects injury risk and how to manage this risk at an individual level.

2.6.1 Individual Sports

In 1978, the relationship between training load and injury had begun to be explored in populations of runners [92]. James et al. [92] suggested that the “vast majority of injuries among long distance runners are the results of improper training” (p. 49), while also proposing that large running volumes were associated with a wide variety of overuse syndromes or injuries [92]. In further work [93], injury rates were observed for long-distance/marathon and sprinters and middle-distance runners over a 1-year period. In marathon runners, a significant correlation existed between the injury rate in any given month, and distance covered in the preceding month (r = 0.59) [93]. Further, the most common injury-provoking factor (72%) was a “training error” alone, such as a large increase in volume or intensity, or with a combination of factors [93]. In more recent work [94, 95], studies have examined the association between sudden increases in weekly running volume and running-related injuries in novice runners. Specifically, novice runners who increased their weekly running volume by greater than 30% over a 2-week period were more vulnerable to sustaining a running-related injury than those who increased their volume by less than 10% [95].

2.6.2 Team Sports

Nick Murray

Load and Injury in AFL
Several studies have monitored and investigated the relationship between workload and incidence of injury in different sports. These include but are not limited to: Australian football [24, 25, 87, 96-99], rugby league [15-17, 21, 100-104], rugby union [10, 105-107], Gaelic football [27, 108], cricket [14, 109], soccer [110, 111], running [92-95], and basketball [112]. A summary of the studies that have investigated the relationship between workload and injury in team sport athletes is displayed in Table 1.
<table>
<thead>
<tr>
<th>Study</th>
<th>Participants</th>
<th>Sport/Level</th>
<th>Variables</th>
<th>Methods</th>
<th>Statistics</th>
<th>Results</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lee et al. (2001)</td>
<td>[106] 80</td>
<td>Semi-professional rugby union</td>
<td>Physical activity levels, number of weeks and sessions completed, and duration of other physical activities completed.</td>
<td>Participants were required to complete a questionnaire following the preseason phase to provide information on training load and injury to researchers.</td>
<td>Cox's proportional hazards regression was used to examine the effects of previous injury, and preseason physical activity in relation to time to first injury.</td>
<td>A 3.9% relative increase in the risk of injury over the season was reported for each additional preseason training week attended.</td>
<td>Surveys may have missing data, along with their subjective nature. Measures used may lack sensitivity.</td>
</tr>
<tr>
<td>Anderson et al. (2003)</td>
<td>[112] 12</td>
<td>Collegiate basketball</td>
<td>Training load, training monotony and training strain using session rating of perceived exertion (RPE).</td>
<td>Participants were required to complete a questionnaire following each session comprising questions related to their perceived exertion of the session.</td>
<td>A Pearson Product Moment correlation was performed on the data to determine the strength of the relationship between the training loads, monotony, and injuries or illnesses.</td>
<td>Increases in injuries occurred during times of increased training loads, particularly during the first 2 weeks of preseason and immediately subsequent to holidays.</td>
<td>Small sample size. Surveys may have been completed by players rather than testers.</td>
</tr>
<tr>
<td>Dennis et al. (2003)</td>
<td>[113] 90</td>
<td>Professional cricket</td>
<td>Balls bowled (external workload)</td>
<td>Workload data were gathered through examining fixture scorecards, along with surveillance at training sessions. Injury data was also collected.</td>
<td>Comparison for the risk of injury was made for workload variables and considered either low or high. Risk ratios were estimated using 2x2 frequency tables.</td>
<td>Players with &lt;2 and &gt;5 days between sessions had an increased risk of injury when compared with those between 3 and 4 days. Those who bowled between 123 and 188 deliveries per week had a decreased risk.</td>
<td>Training workload data limited due to subjective collection. No quantification of intensity of balls bowled.</td>
</tr>
<tr>
<td>Gabbett (2004)</td>
<td>[104] 220</td>
<td>Sub-elite rugby league</td>
<td>Training load (session RPE * duration). Height, mass, skinfolds, vertical jump, agility, maximal aerobic power, and 10m, 20, and 40m sprint time.</td>
<td>Training load, injuries, and physical fitness data were recorded across a three-year period, where load was progressively increased during preseason and decreased during in-season.</td>
<td>A two-way ANOVA was used to assess changes in physical characteristics as age differed. Injury incidence was calculated by dividing the total number of injuries by the total exposure hours.</td>
<td>Training loads were lower in the final two seasons, and injury incidence was the greatest during the first season. Increases in maximal aerobic power were observed across the three seasons.</td>
<td>Playing performance was not analysed due to limited resources.</td>
</tr>
</tbody>
</table>

Table 1. Summary of studies investigating the relationship between workload and injury in team sport athletes.
<table>
<thead>
<tr>
<th>Study</th>
<th>Participants (n)</th>
<th>Sport/Level</th>
<th>Variables</th>
<th>Methods</th>
<th>Statistics</th>
<th>Results</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gabbett (2004)</td>
<td>100</td>
<td>Semi-professional rugby league</td>
<td>Training load (session RPE * duration)</td>
<td>Fitness staff collected session RPE data following each training session and match.</td>
<td>Pearson's product moment correlation coefficients were used to determine the strength of the relationship between variables.</td>
<td>A significant relationship was observed between changes in training load, intensity, duration, and load. Changes in injuries were correlated with intensity and duration.</td>
<td>Session RPE and exposure were the only significant variables. No quantification of intensity of balls bowled.</td>
</tr>
<tr>
<td>Dennis et al. (2005)</td>
<td>44</td>
<td>Junior professional cricket</td>
<td>Balls bowled (external workload)</td>
<td>Players gathered workload and injury data through a self-reporting diary system.</td>
<td>Risk ratios were estimated using 2x2 frequency tables.</td>
<td>Injured bowlers bowled significantly more than non-injured bowlers. Bowlers with less time between sessions were at an increased risk of injury.</td>
<td>Training workload data limited due to subjective collection. No quantification of intensity of balls bowled.</td>
</tr>
<tr>
<td>Gabbett et al. (2007)</td>
<td>183</td>
<td>Sub-elite rugby league</td>
<td>Training load (session RPE * duration), Height, mass, skinfold thickness, vertical jump, agility, maximal aerobic power, and sprint time.</td>
<td>Participants were assessed for fitness data, while individual training load and injury data was divided into pre-season, early competition, and late competition phases.</td>
<td>Individual training load, fitness, and injury data were modelled using a logistic regression model with a binomial distribution and logit link function.</td>
<td>A 1.50-2.85 increase in the odds of injury for each arbitrary unit increase in training load was shown. Increases in load increased the odds of injury during the pre-season.</td>
<td>No information provided on the dose-response relationship. Not representative of a professional training stimulus.</td>
</tr>
<tr>
<td>Brooks et al. (2008)</td>
<td>502</td>
<td>Professional rugby union</td>
<td>Exposure time including number of sessions, and the type and volume of sessions.</td>
<td>Fitness staff recorded individual match and training exposure time using a standard reporting form on a weekly basis.</td>
<td>Weekly training volumes were divided to correspond equal frequency quintiles. Incidences and severity of injuries were calculated, and reported as injuries per 1,000 hours of exposure.</td>
<td>Higher training volumes did not increase the incidence of training or match injuries. Higher training volumes resulted in an increase in severity of match injuries.</td>
<td>The use of time as their sole workload variable.</td>
</tr>
<tr>
<td>Cameron et al. (2007)</td>
<td>183</td>
<td>Sub-elite rugby league</td>
<td>RPE*duration, Training load (session RPE * duration)</td>
<td>Players gathered workload and injury data through a self-reporting diary system.</td>
<td>Risk ratios were estimated using 2x2 frequency tables.</td>
<td>Injured bowlers bowled significantly more than non-injured bowlers. Bowlers with less time between sessions were at an increased risk of injury.</td>
<td>Training workload data limited due to subjective collection. No quantification of intensity of balls bowled.</td>
</tr>
<tr>
<td>Cameron et al. (2004)</td>
<td>100</td>
<td>Professional rugby union</td>
<td>Exposure time (9-1 hours per week)</td>
<td>Fitness staff collected session RPE data following each training session and match.</td>
<td>Pearson's product moment correlation coefficients were used to determine the strength of the relationship between variables.</td>
<td>A significant relationship was observed between changes in training load, intensity, duration, and load. Changes in injuries were correlated with intensity and duration.</td>
<td>Session RPE and exposure were the only significant variables. No quantification of intensity of balls bowled.</td>
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<td>Study</td>
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<td>Sport/Level</td>
<td>Variables</td>
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<td>Gabbett (2010) [21]</td>
<td>91</td>
<td>Professional rugby league</td>
<td>Training load (session RPE * duration)</td>
<td>Training load and injury data were collected from the first two years of a two-year period, and injury incidence was calculated over a pre-season period.</td>
<td>A logistic regression model with a binomial distribution (injury vs. no injury) and logit link function was used to determine if injuries could be predicted and prevented.</td>
<td>Players were 50-80% likely to sustain a preseason injury with a load range between 3,000-5,000 units. The percentage of true positive predictions was 62.3% (n = 121).</td>
<td>Session RPE as the only variable to measure load, unable to predict collision injuries.</td>
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<tr>
<td>Orchard et al. (2009) [107]</td>
<td>38</td>
<td>Professional rugby union</td>
<td>Training and match exposure hours, along with injuries.</td>
<td>Injury incidence and injury rates were calculated and compared with training and match exposure (i.e. minutes). Differences in the incidence of injury between categories from year-to-year were analysed using a chi-squared analysis for trends.</td>
<td>The preseason injury rate increased over the three years, coupled with a reduction in training exposure over the preseason phase.</td>
<td>Time as the only measure of load, other factors associated with injury (i.e. previous injury) not included.</td>
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<tr>
<td>Killen et al. (2010) [106]</td>
<td>36</td>
<td>Professional rugby league</td>
<td>Training load (session RPE * duration). Wellness variables including sleep, food, stress, energy and mood.</td>
<td>Each player’s training time and intensity, along with injury status were recorded over a pre-season period. Analysis included paired t-tests, Spearman and Pearson correlations, one-way ANOVAs. Injury rates were calculated as injuries per 1000 exposure hours and examined using the chi-squared test.</td>
<td>No significant relationship was found between pre-season weekly injury rate and weekly load, nor between load and psychological measures.</td>
<td>Session RPE as the only variable to measure load, a small time sample (i.e. a 14-week pre-season period) was used in this study, a small time sample (i.e. a 14-week pre-season period) was used in this study.</td>
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<tr>
<td>Gabbett et al. (2011)</td>
<td>79</td>
<td>Professional rugby league</td>
<td>Training load (session RPE * duration).</td>
<td>Multiplication, and injuries were recorded across a four-year period, where training loads progressively increased during preseason and decreased during in-season.</td>
<td>Pearson product moment correlation coefficients were used to determine the relationship between training loads and injury incidence.</td>
<td>Training load was significantly related to overall injury, along with non-contact field injury and contact field injury rates.</td>
<td>Session RPE as the only variable to measure load.</td>
</tr>
<tr>
<td>Gabbett et al. (2012)</td>
<td>34</td>
<td>Professional rugby league</td>
<td>GPS variables including discrete acceleration bands, discrete movement velocity bands, and high-intensity effort bouts.</td>
<td>Multiplication, and injuries were recorded across one season, with data collected during the preseason and in-season period.</td>
<td>Frailty model was applied to calculate the relative risk of injury after adjusting for all training data.</td>
<td>Injury risk was 2.7 times higher when 9 m of very high velocity running in a session was exceeded. Greater distances covered in mild, mod, and max accelerations were associated with a decreased risk of injury.</td>
<td>Only one season of data included in the study. GPS as the only load variable, no measure of internal load or response.</td>
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<tr>
<td>Malisoux et al. (2013)</td>
<td>154</td>
<td>Young high-level school sport athletes</td>
<td>Training load (session RPE * duration).</td>
<td>Multiplication, and injuries were recorded.</td>
<td>Cox proportional hazards regression was used to identify injury risk factors among the characteristics of sport participation.</td>
<td>Injury rates were calculated as injuries per 1000 exposure hours. Intensity of sport was significantly greater in the week prior to injury than the preceding 4 weeks.</td>
<td>Self-reported intensity scores by young, inexperienced athletes may not be accurate. Low compliance of data collection.</td>
</tr>
<tr>
<td>Rogalski et al. (2013)</td>
<td>46</td>
<td>Professional Australian football</td>
<td>Training load (session RPE * duration) and all non-contact time-loss injuries were recorded.</td>
<td>Multiplication, and injuries were recorded.</td>
<td>Logistic regression model was used to model workload and injury data. Odds ratios were reported against a reference group of the lowest load range.</td>
<td>Larger 1- and 2-week increases in training load were associated with an increased risk of injury. Previous 1- and 2-week changes in training load were moderate.</td>
<td>Only one season of data included in the study. Session RPE as the only variable to measure load.</td>
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<tr>
<td>Colby et al. (2014)</td>
<td>46</td>
<td>Professional Australian football</td>
<td>GPS variables including total distance and sprint distance, along with other proprietary GPS metrics.</td>
<td>Workload data and injury incidence were monitored across pre- and in-season phases.</td>
<td>Multiple regression was used to compare cumulative and absolute change in workloads between injured and non-injured players.</td>
<td>During preseason, 3 weekly total distance, and 3 weekly sprint distance were most indicative of increased injury risk.</td>
<td>Proprietary GPS metrics used in the study. No use of internal workloads and distance were monitored.</td>
</tr>
<tr>
<td>Hulin et al. (2014)</td>
<td>28</td>
<td>Professional cricket</td>
<td>Balls bowled (external) and training load (internal; session RPE * duration).</td>
<td>Workload data were quantified using balls bowled and session RPE, and subsequently modelled as acute:chronic workload ratios.</td>
<td>The likelihood of sustaining an injury was analysed using a binary logistic regression, with injury as the dependent variable. Relative risk was used to quantify increased or decreased risk. An ACWR &gt; 1.5 was associated with a significantly increased injury risk for both internal and external workload.</td>
<td>Small sample size of fast bowlers, although it is a representative sample.</td>
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<tr>
<td>Orchard et al. (2014)</td>
<td>235</td>
<td>Professional cricket</td>
<td>Balls bowled (external workloads)</td>
<td>Workload patterns were monitored between 5 and 26 days to determine if there was an increased risk in the subsequent 28 days to the workload performed.</td>
<td>95% confidence intervals and relative risks were used to calculate differences between injury risk and low and high workload groups. Bowlers who bowled &gt; 50 overs in a match were at an increased risk of injury during the next 28 days.</td>
<td>Balls bowled as the only measure of workload.</td>
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<tr>
<td>Carey et al. (2016)</td>
<td>53</td>
<td>Professional Australian football</td>
<td>GPS variables including total distance, meters per minute, and moderate and high-speed running. Session RPE, and player load were also used.</td>
<td>Workload data were quantified using GPS, and modelled as acute:chronic workload ratios using multiple acute and chronic time windows.</td>
<td>Acute:chronic workload ratios were modelled against injury risk using a quadratic regression, and each parameter combination was compared for injury likelihood fit ($R^2$). The 3 days:21 days acute:chronic time window discriminated between high- and low-risk athletes. The choice of acute time window significantly influenced model performance.</td>
<td>Only a single sport considered in this study. Multiple non-modifiable risk factors (i.e. age, experience) were considered beyond the scope of this study.</td>
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<td>Cross et al. (2016)</td>
<td>173</td>
<td>Professional rugby by union</td>
<td>Training load (session RPE * duration)</td>
<td>Fitness staff collected session RPE data following each field and gym-based session.</td>
<td>Generalized estimating equations were used to model the association between in-season training load and injury.</td>
<td>Injury risk increased with a 2 x SD increase in 1-week loads and week-to-week change in load. A reduction in injury risk was found with moderate loads across four weeks.</td>
<td>Other factors associated with injury (i.e. previous injury, psychological stressors) were not included.</td>
</tr>
<tr>
<td>Caparros et al. (2016)</td>
<td>44</td>
<td>Professional basketball</td>
<td>Sports performance during competition, injury rates, and total time exposure (training and matches)</td>
<td>Data was collected over 7 seasons on exposure time, injury, and performance measures.</td>
<td>Pearson's correlation was used to compare team values and outcome parameters (performance, injury rate or exposure time).</td>
<td>There was a strong positive correlation between exposure time and injury incidence, exposure time and performance measures, and total number of injuries and performance.</td>
<td>Time as the only measure of workload included in the study.</td>
</tr>
<tr>
<td>Duhig et al. (2016)</td>
<td>51</td>
<td>Professional Australian football</td>
<td>GPS-derived running distances and session-based RPE values for all matches and training sessions.</td>
<td>All hamstring injuries were documented, and players high-speed running modelled relative to their individual average.</td>
<td>Independent t-tests were used to determine differences in workload between injured and non-injured players. Paired t-tests were used to compare seasons.</td>
<td>Higher than 'typical' high-speed running values were associated with increased injury risk across multiple weeks.</td>
<td>A small number (n=22) of injuries used in the small number (n=22) of injuries used in the study.</td>
</tr>
<tr>
<td>Hulin et al. (2016)</td>
<td>28</td>
<td>Professional rugby league</td>
<td>Total distance measured via GPS.</td>
<td>Workload data were quantified using total distance, and modelled as acute and chronic workloads, along with the ACWR.</td>
<td>The likelihood of sustaining an injury was analysed using a binary logistic regression, with injury as the dependent variable. Relative risk was used to quantify increased or decreased risk.</td>
<td>An ACWR &gt; 1.5 was associated with an increased injury risk. High chronic loads provided a protective effect against injury during periods of short turnaround between matches.</td>
<td>Total distance as the only measure of workload included in the study. Other factors associated with injury (i.e. previous injury, psychological stressors) were not included.</td>
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<tr>
<td>Hulin et al. (2016)</td>
<td>53</td>
<td>Professional rugby league</td>
<td>Total distance measured via GPS. Weekly distance above 24 km.hr was recorded.</td>
<td>The likelihood of sustaining an injury was analysed using a binary logistic regression, with injury as the dependent variable. Relative risk was used to quantify increased or decreased risk. Players with a high chronic workload were more resistant to injury with moderate ACWR values, and less resistant to injury with a very high ACWR. Other factors associated with injury (i.e. previous injury, psychological stressors) were not included.</td>
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<tr>
<td>Malone et al. (2016)</td>
<td>37</td>
<td>Professional Gaelic football</td>
<td>GPS variables of distance between 10–24 km.hr-1 and above 24 km.hr-1.</td>
<td>Workload data were modelled multiple ways for the two speed bands utilised, and prospective hamstring injuries were recorded. Receiver operator characteristic curve analyses were performed and the relative risk of subsequent hamstring injury calculated for absolute and relative running exposure. Weekly distance above 24 km.hr-1 had the largest influence on the risk of hamstring injury. Predictive capabilities were limited, despite the significant increases in relative risk.</td>
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<tr>
<td>Ruddy et al. (2016)</td>
<td>220</td>
<td>Professional Australian football</td>
<td>GPS variables of distance between 10–24 km.hr-1 and above 24 km.hr-1.</td>
<td>Workload data were modelled multiple ways for the two speed bands utilised, and prospective hamstring injuries were recorded. Receiver operator characteristic curve analyses were performed and the relative risk of subsequent hamstring injury calculated for absolute and relative running exposure. Weekly distance above 24 km.hr-1 had the largest influence on the risk of hamstring injury. Predictive capabilities were limited, despite the significant increases in relative risk.</td>
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<th>Participants (n)</th>
<th>Type of Sport</th>
<th>Variables</th>
<th>Methods</th>
<th>Statistics</th>
<th>Results</th>
<th>Limitations</th>
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<tr>
<td>Veugelers et al. (2016)</td>
<td>45</td>
<td>Professional Australian football</td>
<td>Training load (session RPE * duration) and all time-loss injuries were recorded. Training load was quantified using four methods involving rating of perceived exertion. This was recorded along with injury and illness over the duration of one preseason.</td>
<td>A logistic regression model was used to investigate the relationship between training load and injury, with the low training load group considered as the reference group.</td>
<td>A general trend existed where lower odds of injury and illness were observed in the high training load groups.</td>
<td>Session RPE as the only variable to measure load Other factors associated with injury (i.e. previous injury, psychological stressors) were not included.</td>
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<tr>
<td>Windt et al. (2016)</td>
<td>30</td>
<td>Professional rugby league</td>
<td>Total number of sessions completed, along with GPS variables including total distance, high-speed distance, and % of distance covered at high-speed. Preseason training workload, measured via sessions completed was measured, and players were monitored during the following in-season period to assess in-season training and match workload. Multilevel logistic regression models were used to determine injury likelihood in the current and subsequent week. Odds ratios were used as effect size measures to determine the changes in injury likelihood. 10 additional preseason sessions completed was associated with a 17% reduction in the odds of injury in the subsequent week. Increased participation resulted in a lower percentage of games missed.</td>
<td>- Discrepancies between injury and training load, high-speed distance, and % of distance covered at high-speed. - Discrepancies between injury and training load, high-speed distance, and % of distance covered at high-speed. - Discrepancies between injury and training load, high-speed distance, and % of distance covered at high-speed.</td>
<td>- A small sample size of injuries (40) - Limited GPS use to velocity based measures, without any information on accelerations, decelerations, etc.</td>
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<tr>
<td>Bowen et al. (2017)</td>
<td>32</td>
<td>Elite youth football</td>
<td>GPS variables including total distance, high-speed distance, total load, and accelerations. Workload data were quantified using GPS technology from all on-field training sessions and matches. Multiple regression analyses were used to compare cumulative workload and ACWR ratios between injured and non-injured players. A very high number of accelerations over 3 weeks was associated with increased injury risk. High acute loads, coupled with low chronic loads increased the risk. Non-modifiable factors (i.e. age and injury history) were not taken into account.</td>
<td>- A small sample size of players and injuries - Small sample size of players and injuries - Small sample size of players and injuries</td>
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<tr>
<td>Carey et al. (2017)</td>
<td>75</td>
<td>Professional Australian football</td>
<td>GPS variables including total distance, moderate-speed running, session RPE, and player load were also used. Injury prediction models were built for non-contact, non-contact time loss and hamstring specific injuries. Injury predictions were built, and subsequently evaluated using the area under the receiver operator characteristic (AUC). Predictive performance was marginally better than chance for non-contact and non-contact time loss injuries. The best performing model was a multivariate logistic regression for hamstring injuries.</td>
<td>- High player turnover during study - High player turnover during study - High player turnover during study</td>
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<th>Type of sport</th>
<th>Variables</th>
<th>Methods</th>
<th>Results</th>
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<tr>
<td>Colby et al. (2017) [122]</td>
<td>70</td>
<td>Professional Australian football</td>
<td>GPS variables including total distance and sprint distance. Individual injury risk factors (i.e. age, previous injury history) were also included. Individual player injury data was collected across four seasons, along with player workloads using GPS during the preseason period.</td>
<td>A generalized estimating equation with a binary logistic function modelled risk factors with non-contact injury. Odds ratios were also calculated to determine relative injury risk.</td>
<td>Low cumulative total distances in late preseason were associated with significantly greater injury risk during the in-season phase.</td>
</tr>
<tr>
<td>Harrison et al. (2017) [124]</td>
<td>60</td>
<td>Sub-elite Australian football</td>
<td>Training load (session RPE * duration). Injury information and 2km time trial time were also recorded.</td>
<td>Individual training load, aerobic fitness and injury data was compared with non-contact soft-tissue injury. The likelihood of sustaining an injury was analysed using a logistic regression model, with injury likelihood data presented as odds ratios.</td>
<td>Players with low preseason training loads had the highest injury rates, while large two-week and spikes in weekly load significantly increased injury risk.</td>
</tr>
<tr>
<td>Jaspers et al. (2017) [125]</td>
<td>35</td>
<td>Professional soccer</td>
<td>External workloads from GPS included; total distance, high-speed distance, accelerations, and decelerations. Internal workloads using RPE were used. Cumulative loads, along with the ACWR were calculated and players were divided into low, medium, and high groups to assess differences in injury risk.</td>
<td>Generalized estimating equations were applied to analyse the relationship between injury and load indicators in the subsequent week.</td>
<td>Higher cumulative loads demonstrated in the previous week were associated with increased injury risk. A high cumulative load in the previous week was associated with a higher ACWR and significant increases in injury risk.</td>
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<td>Lu et al. (2017) [126]</td>
<td>45</td>
<td>Professional soccer</td>
<td>Exposure time, along with internal workloads (session RPE multiplied by duration), coupled with external workloads (using GPS technology).</td>
<td>Training monotony and strain, along with the acute:chronic workload ratio were calculated for all variables and modelled against injury likelihood. A one-way ANOVA was used to assess differences in the weeks prior to and at time of injury. Sensitivity and specificity were used to assess the accuracy of a workload profile leading to injury.</td>
<td>Absolute and relative exposure was higher in the 3 weeks before an injury occurred. The acute:chronic workload ratio for session RPE was more sensitive than very high-speed running.</td>
</tr>
<tr>
<td>Malone et al. (2017) [127]</td>
<td>48</td>
<td>Professional soccer</td>
<td>Training load (session RPE * duration). Injury information and Yo-YoIR1 were also recorded.</td>
<td>Weekly workload measures and time loss injuries were recorded during the duration of the study. Workload and injury were modelled against injury data using logistic regression. Odds ratios were used to compare to a reference group.</td>
<td>Players with better aerobic capacity were better able to tolerate increases in workload. A moderate ACWR (1.00–1.25) had a lower risk of injury than a low ACWR (&lt; 0.85).</td>
</tr>
<tr>
<td>Malone et al. (2017) [128]</td>
<td>37</td>
<td>Professional soccer</td>
<td>Internal workloads (session RPE multiplied by duration), coupled with external workloads (using GPS technology).</td>
<td>Internal workloads were recorded in conjunction with external workloads to quantify distance, while all lower limb injuries were recorded. Workload and injury were modelled against injury data using logistic regression. Odds ratios were used to compare to a reference group.</td>
<td>Players who completed moderate high speed and sprint distance had a lower injury risk than those who completed low amounts. Higher chronic workloads offered a protective effect.</td>
</tr>
<tr>
<td>Moller et al. (2017) [129]</td>
<td>679</td>
<td>Elite youth handball</td>
<td>Handball load (measured as training and competition hours)</td>
<td>Players reported their training and competition loads, and injury status weekly. Shoulder isometric rotational and adduction strength, ROM, and scapular control was recorded at the start of testing. Cox proportional hazards regression with frailty was used to estimate hazard ratios using calendar weeks as time-scale. Primary exposure was included in the analysis as a time-dependent exposure.</td>
<td>An increase in handball load (&gt;60%) was associated with increased shoulder injury rates compared with a reference group. Low frequency of shoulder injuries throughout the study Playing position and previous injuries not included as risk factors.</td>
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<td>Stares et al. (2017)</td>
<td>70</td>
<td>Professional</td>
<td>Australian football</td>
<td>Workload data were modelled using various ACWR timeframes, and then analysed to determine the injury risk in the subsequent month.</td>
<td>Poisson regression with robust errors within a generalized estimating equation were utilised to determine incidence rate ratios.</td>
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<tr>
<td>Warren et al. (2017)</td>
<td>29</td>
<td>Junior professional</td>
<td>Cricket</td>
<td>Bowling workloads were modelled using acute and chronic workloads, along with the acute:chronic workload ratio. A generalized linear mixed-effects model was used to model the association between workloads and injury risk in the subsequent 4-week period.</td>
<td>High ACWR values (&gt;1.42) were associated with a significant increase in subsequent injury risk. However, higher chronic workload lessened the risk when a high ACWR was shown. Self-reported bowling workloads as the sole measure of workload. Small, although representative sample size of fast bowlers.</td>
</tr>
<tr>
<td>Watson et al. (2017)</td>
<td>75</td>
<td>Amateur adolescent</td>
<td>Soccer</td>
<td>Training load (session RPE * duration). Wellness variables including sleep, food, stress, energy and mood. Workload, wellness, and injury data were collected over a 20-week season and modelled using injury and no injury as the outcome variables. Poisson regression models were developed to predict daily injuries and illnesses using wellness and training load as predictors.</td>
<td>Days with an injury had lower mood scores and high training load values. Similarly, scores and training days were negatively correlated.</td>
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</table>
Early research in team sports examined the relationship between workloads and injury in sub-elite rugby league players [100]. Significant correlations were reported between changes in match intensity ($r = 0.74$), match duration ($r = 0.86$), and match load ($r = 0.86$) and match injury. In addition, changes in the incidence of training injuries were significantly associated with changes in training intensity ($r = 0.83$), training duration ($r = 0.79$), and training load ($r = 0.86$) [100]. The highest incidence of injuries (205.6 per 1000 training hours) was recorded in February, which coincided with the end of pre-season where training load was the highest.

In further work, Gabbett [104] investigated whether reductions in pre-season training loads, over a three-year period, reduced the incidence of training injuries in sub-elite rugby league players. Following the initial pre-season (2001), training loads were reduced in the second (2002), and third (2003) years, through reductions in training duration and training intensity, respectively. Reductions in training loads were associated with significant reductions in training injury rates [104]. No studies since have replicated these findings, which suggests that this finding may be an anomaly, as it is also in contrast with recent findings, which suggest that moderate-to-high chronic workloads may offer a protective mechanism against the risk of non-contact soft-tissue injury [17, 27, 132]. It is possible that the players were overtraining in the first year of the study, resulting in (1) higher injury rates, and (2) a diminished improvement in aerobic capacity which has shown to decrease injury risk [108].

Similar work conducted on professional rugby union players failed to find a significant relationship between high training volumes (> 9.1 hours per week) and the incidence of injury sustained during training or competition [105]. However, a positive trend between high training volumes and the increased severity of match injuries was reported, resulting in a significant increase in the number of days missed due to injury. Further investigations [107] found that reductions in training volume led to a reduced total injury rate (albeit not
significant), and reduced in-season ($\chi^2 = 2.89, p = 0.09$), and pre-season ($\chi^2 = 12.7, p < 0.01$) injury rates [107].

Gabbett and Domrow [101] found that an increase in training load during the pre-season training phase was associated with an increase in the odds of injury. They proposed that the high incidence of overuse and lower-limb injuries in the pre-season phase supports the notion that increases in injury risk during the pre-season are closely associated with increases in workload [101]. Interestingly, they found that during the early-competition phase, increases in weekly workload from 175 to 620 arbitrary units resulted in no further increase in injury incidence [101]. In further work [103], the relationship between differing running loads (i.e. low- and high-intensity efforts) and soft-tissue injury in elite rugby league players was examined. It was reported that when very high-velocity running (i.e. sprinting) exceeded 9 m in a single training session, injury risk was 2.7 times higher. The authors proposed that greater amounts of very high-velocity running were coupled with an increased risk of lower body soft-tissue injury [103].

The pre-season period of competition is seen as a crucial time to develop the physical qualities required for a particular sport to enable an athlete to not only play, but compete, in match-play [97]. With this in mind, Windt et al. [15] examined whether elite rugby league players who completed a greater proportion of the planned pre-season training were more or less likely to sustain an injury in the subsequent season. A significant correlation was found between the number of full pre-season training sessions a player completed, and the number of full in-season training sessions a player completed ($r = 0.59, p < 0.001$). They also found that there was a significant association between pre-season sessions completed and the
percentage of in-season matches missed through injury ($r = -0.40$, $p < 0.05$). A greater pre-
season training participation was coupled with a decreased injury risk in the subsequent in-
season period (OR = 0.82, 95% CI 0.69 to 0.97) [15]. The authors concluded that in this
cohort of elite rugby league players that (1) a greater number of pre-season sessions 
completed resulted in a reduced likelihood of injury during the competitive period, (2) 
players who completed a greater amount of pre-season training sessions also completed a 
greater amount of in-season training sessions, and (3) players who completed a greater 
amount of pre-season training sessions missed fewer games due to injury.

Recently, a study in professional rugby union explored the association between in-season 
training load measures and injury risk over one season [10]. In this study, training load was 
measured using session-rating of perceived exertion (RPE) for all field and gym based 
sessions, while all time-loss injuries were recorded. They [10] found that injury risk increased 
linearly with both 1-week loads (OR = 1.68, 95% CI 1.05–2.68) and week-to-week changes 
in load (OR = 1.58, 95% CI 0.22–1.38), with a 2-SD increase in these variables (1245 AU 
and 1069 AU, respectively). Interestingly, they also found that when compared with the 
weekly low load reference group (< 3684 AU), a likely beneficial reduction in injury risk 
(OR = 0.55, 95% CI 0.22–1.38) was found in the intermediate load group (5932 – 8651 AU). 
These findings [10, 14, 101, 103] highlight the need to carefully monitor training loads in 
order to minimise the incidence and risk of training-related injuries.

2.6.3 Australian Football

Rogalski et al. [25] examined the relationship between training workload and injury risk and 
found that larger 1-weekly (> 1750 AU, odds ratio [OR] = 2.44 – 3.38), 2-weekly (> 4000
AU, OR = 4.74), and previous-to-current week changes in load (> 1250 AU, OR = 2.58) were significantly (p < 0.05) related to larger injury risk during a season. It was also reported that during a pre-season training block, 3-weekly distance covered (OR = 5.489, p = 0.008) and 3-weekly sprint distance (OR = 3.667, p = 0.074) were associated with a higher injury risk [24].

A study in Australian football [97] compared the use of four different measures of session-RPE training load and their relationship to injury and illness in an elite cohort of players. Interestingly, the authors reported that there was a general trend that a lower injury likelihood existed for those in the high training load group, compared with the low training load group [97]. They suggested that the lower injury likelihood may be due to those players within the high training load group working at an optimal level to enhance their physical qualities, which subsequently reduces their risk of injury. Further, those within the low training load group may exhibit a higher risk of injury due to an inadequate exposure to sufficient workload [97]. It is difficult to draw strong conclusions from either of these studies [96, 97] however, due to a small sample of injuries recorded (n = 5 and n = 13, respectively). Both studies [96, 97] suggest that the accurate monitoring of training load using session-RPE has the potential to provide some information on when an injury may occur, however more research is needed to strengthen these findings [96, 97]. With the physical demands of AF increasing [64], an increased emphasis has been placed on quantifying loads during training and competition. Given that soft-tissue injuries remain the most common injury in the game [6], and the association shown between workloads and injury [24-26, 101-103], the increased emphasis on training monitoring and workload management is warranted.
More recently, the volume of workload completed during the pre-season training phase and its association with subsequent injury during the pre-season, pre-competition, and in-season phases has been assessed [122]. It was reported that the pre-competition phase, or the period between the pre- and in-season, demonstrated the highest injury risk period across an AFL season. This is the time where players experience their first exposures to competition match play, which is likely an underlying influence on the increased injury risk during this period [122]. In a further finding, a significant relationship was reported whereby players who completed low cumulative workloads during the pre-season, and pre-competition phase were ~5 and ~6 times more likely, respectively, to sustain a non-contact injury during the in-season period [122]. Extending on this work, the association between workload, subjective player wellness, and musculoskeletal screening measures have been examined [123]. Similar to previous work [16, 122], low cumulative workloads across a 3- and 4-week period were associated with the greatest injury risk in the subsequent week [123]. In a multivariate analysis that considered multiple factors that influence the workload-injury relationship, the interaction between low chronic workload and a very high acute total distance, and a low session-RPE chronic workload along with a low session-RPE acute:chronic workload ratio (ACWR) had the greatest injury risk [123]. In both instances, low chronic workloads, coupled with both high and low ACWR ranges were associated with increases in injury risk. This could be due to a considerable de-load, making a player more susceptible to sharp increases in workload, suggesting the player may not be ready to tolerate the physical demands required of their sport. This work highlights that (1) the relationship between workload and injury is largely multi-factorial, and (2) chronic workload plays an important role in mediating the relationship between workload and injury [123].
2.6.4 The Acute:Chronic Workload Ratio

In a recent review in the British Journal of Sports Medicine, Gabbett [9] proposed a model where non-contact injuries, which are typically viewed as preventable or ‘training-load error’ injuries [20], are not caused by training itself, but rather an inappropriate training program which an athlete is not prepared to complete [9]. In a further review, Windt & Gabbett [26] proposed an updated workload-injury aetiology model, inclusive of the effects of workload on athletes, where positive and negative adaptations are controlled by both total workloads, as well as the interaction of intrinsic (i.e. age, neuromuscular control, previous injury, strength) and extrinsic (i.e. playing surface, equipment) risk factors. Specifically, in relation to workload, a model that takes into account the short-term workload (i.e. acute workload), along with the medium-term workload (i.e. chronic workload) has been proposed to quantify the relationship between workload and injury (i.e. the acute:chronic workload ratio) [9, 133]. With advancements in knowledge surrounding the workload-injury relationship, we now know that (1) appropriate high training loads are associated with lower injury rates [9, 10, 14, 16, 17, 27, 108, 111], and (2) it is important to monitor both the recent (i.e. acute) and medium-term (i.e. chronic) workloads when considering the relationship between workload and injury [9, 10, 14, 16, 17, 27, 108, 111]. Based on these findings, it appears crucial to measure the acute:chronic workload ratio “… as a best practice predictor of training-related injuries” (p.273) [9].

The original work completed by Hulin et al. [14] determined whether acute and chronic workload, and ‘training-stress balance’ (a term now more commonly referred to as the ‘acute:chronic workload ratio’) was associated with injury risk in elite cricket fast bowlers. In this study, workloads were estimated in two ways, (1) external workload measured by balls...
bowled per week, and (2) internal workload measured by session-RPE (RPE score x training duration). An injury was included in the analysis if it was a non-contact soft-tissue injury where a player missed a match, or missed more than one training session over a one-week period, no specific injury regions were considered. They reported that large increases in acute bowling workload (i.e. balls bowled), represented by a high acute:chronic workload ratio, were associated with an increased risk of injury in the week following exposure (Relative Risk [RR] = 2.1 (CI 1.81 to 2.44), \( p = 0.01 \)) [14]. In addition, a high acute:chronic workload ratio for internal workload was associated with an increased risk of injury in the subsequent week (RR = 2.2 (CI 1.91 to 2.53), \( p = 0.009 \)). Specifically, fast bowlers who exhibited a high acute:chronic workload ratio of > 2.0 had a significantly greater relative risk of injury compared to fast bowlers with an acute:chronic workload ratio between 0–0.49 (RR = 3.4 (CI 1.56 to 7.43, \( p = 0.032 \)), and 0.50–0.99 (RR = 4.5 (CI 3.43 to 5.90), \( p = 0.009 \)) [14]. The authors proposed that elite cricket fast bowlers were at a significantly increased risk of injury in the week following exposure to a high acute:chronic workload ratio. They also suggested that higher chronic external workloads were associated with a decreased risk of injury in this cohort [14]. In a further investigation in the National Development Programme for fast bowlers using the same injury definitions [109], earlier findings [14] were confirmed whereby ‘spikes’ in workload, resulting in a high ACWR, were associated with a significant increase in injury risk. However, this work also suggests the importance of moderate-to-high chronic workload in the mediation of the relationship between a high ACWR and injury risk [109], which is also consistent with previous work [17, 122, 123].

In subsequent work in rugby league, the acute:chronic workload ratio and its effect on injury risk was investigated [16, 17]. In the first of these two studies [17], the acute:chronic workload ratio was investigated to determine its predictive capability on non-contact soft-
tissue injury in elite rugby league players using an injury definition where a player was unable to complete full training or missed match time. In the current week, they found that a very high acute:chronic workload ratio (≥ 2.11) was associated with an increased injury risk compared to each lower acute:chronic workload ratio category; acute:chronic workload ratio of ≤ 0.30 (RR = 6.9; likelihood 98%, very likely), acute:chronic workload ratio of 0.31–0.66 (RR = 3.4, likelihood 97%, very likely), acute:chronic workload ratio of 1.03–1.38 (RR = 2.3, likelihood 91%, likely), and an acute:chronic workload ratio of 1.75–2.10 (RR = 2.0, likelihood 77%, likely) [17]. In addition, a novel finding of this study was that a high chronic workload combined with both moderate (1.02–1.18), and moderate-high workload (1.19–1.35) ratios exhibited a smaller risk of injury than a low chronic workload combined with multiple acute:chronic workload ratios [17].

Hulin et al. [16] also investigated acute and chronic workloads in relation to the turnaround time between matches to determine the risk of match injury following short (5 and 6 days) or long (7, 8, and 9 days) recovery between matches in elite rugby league players. Acute and chronic workloads, and the acute:chronic workload ratio were modelled in the same way as earlier research [14, 17] for absolute total distance (m). In respect to chronic workload, a higher value (18.9–22.1 km) was associated with a decreased risk of match injury when compared with moderate-low (RR = 0.27 (CI 0.08 to 0.92); likelihood = 95%, very likely), and low (RR = 0.32 (CI 0.08 to 1.22); likelihood = 90%, likely) chronic workloads [16]. Interestingly, during short turnarounds, a trend existed whereby a lower risk of match injury occurred when chronic workload increased [16]. Further, the risk of sustaining a match injury with a very high acute:chronic workload ratio (≥ 1.62) during a short turnaround was higher than with a moderate-high (RR = 5.80 (CI 1.75 to 19.2); likelihood = 99%, very likely), and low (RR = 3.41 (1.17 to 9.91); likelihood = 96%, very likely) acute:chronic
workload ratio, respectively. Together, these findings [16, 17] provide further support for the workload-injury prevention paradox [9] with higher chronic workloads offering a protective effect against injury when the acute workload is similar to the chronic workload.

Research in Gaelic football has investigated the association between (1) combined session-RPE workload measures and injury risk [108], and (2) chronic workloads and exposure to maximal velocity and subsequent injury risk [27]. In these studies, the injury definition used was; any injury which prevented a player from partaking in full training or match-play for a period of greater than 24 hours. In line with earlier findings [14, 16, 17], players with an acute:chronic workload ratio of > 2.0 were at an increased risk of injury. Two novel findings of this study were (1) when exposed to a high acute:chronic workload ratio (> 1.50), players with only one year of playing experience had a greater risk of injury (OR = 2.22) than players with 2–3 (OR = 0.20), and 4–6 (OR = 0.24) years’ experience, and (2) players with less-developed physical qualities (i.e. aerobic fitness) experienced a greater risk of injury (OR = 1.50–2.50) compared with players with well-developed physical qualities [108]. In the latter study, Malone et al. [27] reported that players who recorded at least one exposure to greater than 95% maximal velocity in a training week experienced a decreased injury risk compared with the reference group of greater than 85% on at least one occasion (OR = 0.12, p = 0.001). Similar to the study by Cross [10], the authors suggested the existence of a “U-shaped” relationship between maximal velocity exposure and injury risk, where both under- and over-exposure to maximal velocity events increase the risk of injury. They reported that players who maintained a higher chronic training load (≥ 4750 AU) were able to tolerate increased distance and exposures to maximal velocity, with these exposures providing a decreased injury risk compared with lower exposures (OR = 0.22, p = 0.026) and distance (OR = 0.23, p = 0.055) [27]. These findings were replicated in further work in elite youth football players.
reporting that progressive increases in chronic workload may offer a protective effect against injury, through developing a tolerance, and therefore resilience, to systematically applied higher workloads.

While these findings have been replicated across multiple sports, the demands of each sport remain unique. For instance in the early work within cricket, Hulin et al [14] examined the relationship between workload and injury using both external (i.e. balls bowled), and internal (session-RPE) workload measures. This is in contrast to further work in rugby league [16, 17], which has examined external workload such as distance run to determine the workload-injury relationship. Similar investigations have utilised external workload measures via GPS technology to assess the demands of the sport, and quantify the workload-injury relationship [15, 27, 111, 127]. While the demands of each sport will remain unique, these workload-injury relationships can be modelled using sport-specific workload data to quantify the workload-injury relationship. Collectively, these findings support the notion that high training workloads, applied appropriately, develop physical qualities that not only allow players to compete at the highest level of their given sport but also aid in protecting players from injury [8, 9, 14, 16, 17, 27, 108].

More recently, the use of the acute:chronic workload ratio calculated using a rolling averages model has been questioned [134]. In an insightful letter, Williams et al. [134] suggested that the use of a rolling averages model, which considers all load within a given chronic workload period as equal, may not be a true representation of the physiological response to workload. Consequently, an exponentially weighted moving averages (EWMA) model to calculate the acute:chronic workload ratio has been proposed. This model places a higher weighting on the
more recent workload performed, coupled with a diminishing weighting placed on the more medium-term load [134]. To date, there is limited evidence to suggest that this model may be better suited to modelling workload than the rolling averages model [135]. Improvements in the way that the acute:chronic workload ratio is calculated may be improved with further research, however the general premise that large spikes in workload are associated with increased injury risk remains the same [14, 16, 17, 108, 111, 127].
2.7 Specific Aims of the Current Research

In light of the literature review, the overall aim of this thesis was to investigate the relationship between workload and injury in professional Australian football players. The specific aims of the research were to;

• Investigate if acute and chronic running workloads, and the acute:chronic workload ratio were associated with subsequent injury risk.

• Investigate the relationship between the proportion of pre-season training completed and subsequent in-season load, match availability, and injury risk in the ensuing season.

• Investigate if any differences exist between the rolling average and exponentially weighted moving average methods of acute:chronic workload ratio calculation and subsequent injury risk.

• Investigate if differences in activity profile exist when data are expressed as both an absolute threshold, and relative to an individual player’s maximum velocity.

• Examine if the use of relative acute and chronic running workloads, and the acute:chronic workload ratio are associated with subsequent injury risk, and how they differ from absolute acute and chronic running workloads.

• Identify key differences in loading patterns between the different methods (rolling average and exponentially weighted moving average) of acute:chronic workload ratio calculation.

• Identify how spikes in workload can occur in one, or both, of the acute:chronic workload ratio calculation methods.

• Investigate the effectiveness of the implementation of a training monitoring system using the acute:chronic workload ratio in a cohort of professional Australian football players over the course of a season.
2.8 Experimental Hypotheses

To address these specific aims, a number of experimental hypotheses were proposed in this program of research. The specific experimental hypotheses were;

(i) Large spikes in acute workload, resulting in a very high acute:chronic workload ratio (i.e. > 2.0) will be associated with significant increases in injury risk.

(ii) A greater amount of pre-season training completed will result in more matches played, and higher workloads maintained during the subsequent in-season period.

(iii) The exponentially weighted moving averages model will be more sensitive for detecting increases in injury likelihood when modelled for the acute:chronic workload ratio.

(iv) The use of relative workloads, calculated at an individual level, will be more sensitive to changes in injury likelihood, particularly at higher velocities.

(v) Differences will exist in loading patterns between the different models of acute:chronic workload ratio calculation.

(vi) A training monitoring system will help reduce the number of spikes in workload a player encounters, and subsequently reduce injury rate.
Chapter 3

Study 1 – Individual and combined effects of acute and chronic running loads on injury risk in elite Australian footballers

This study has been accepted for publication following peer review. Full reference details are:

3.1 Abstract

Objectives: A model that takes into account the current workload, and the workload the athlete has been prepared for, as an acute:chronic workload ratio has been previously used as a novel way to monitor training load and injury risk. The aim of this paper was to investigate the use of this model in Australian football.

Design: Single cohort, observational study.

Methods: Fifty-nine elite Australian football players from one club participated in this two-year study. Global Positioning System technology was used to provide information on running workloads of players. An injury was defined as any non-contact ‘time-loss’ injury. One-week (acute), along with four-week (chronic) workloads were calculated for a range of variables. The size of the acute workload in relation to the chronic workload was calculated as an acute:chronic workload ratio.

Results: An acute:chronic workload ratio of >2.0 for total distance during the in-season was associated with a 5 to 8-fold greater injury risk in the current (relative risk (RR)=8.65, p=0.001) and subsequent week (RR=5.49, p=0.016). Players with a high-speed distance acute:chronic workload ratio of >2.0 were 5 to 11 times more likely to sustain an injury in the current (RR=11.62, p=0.006) and subsequent week (RR=5.10, p=0.014).

Conclusions: These findings demonstrate that sharp increases in running workload increase the likelihood of injury in both the week the workload is performed, and the subsequent week.
3.2 Introduction

Australian Football (AF) is an intermittent team sport, requiring players to perform repeated high-speed (i.e. sprinting, running) and low-speed (i.e. jogging, walking) movements interspersed with physical contacts throughout a match [28, 31]. The ability of players to maintain the required level of physical activity throughout a match is vital for successful performance, with global positioning system (GPS) devices regularly used to monitor activity profiles during competition [1, 30, 31]. An increased emphasis has been placed on quantifying workloads during training and competition, and the relationship between workload and injury [14, 17, 21, 25, 100-102]. Indeed, some have promoted the restriction of players’ workloads in an attempt to limit the training-related stresses, thereby potentially reducing the number of injuries sustained [91].

Originally proposed by Banister [11-13] the fitness-fatigue model states that the training stress placed on an athlete results in two contrasting responses – fitness and fatigue. Based on these early investigations, a novel model comparing acute workload (i.e. 1-week workload) and chronic workload (i.e. 4-week rolling average acute workload) has been used to predict performance and injury [9, 14, 16, 17]. Preparedness represents the difference between a positive function (i.e. fitness) and a negative function (i.e. fatigue), where chronic workload represents ‘fitness’ and acute workload represents ‘fatigue’ [9]. The fitness after-effect results in a positive physiological response and in turn improved performance [11-13], whereas the fatigue after-effect results in a negative physiological response, decreased performance, and potentially a subsequent increase in injury risk [9, 14, 17]. The difference between the positive physiological response and the negative physiological response provides either a low (chronic workload is greater than the acute workload) or high (acute workload is greater than the chronic workload) acute:chronic workload ratio [11, 13, 102].
In sub-elite rugby league players, Gabbett and Domrow [101] demonstrated an increase in the likelihood of injury during the pre-season (odds ratio [OR]=2.12, p=0.01), early competition (OR=2.85, p=0.01), and late competition (OR=1.50, p=0.04) phases, for every increase in a log (150 arbitrary units [au]) of workload, measured using the session rating of perceived exertion (RPE). Rogalski et al. [25] found that larger 1-weekly (>1750 au, OR=2.44–3.38), 2-weekly (>4000 au, OR=4.74), and previous-to-current week (>1250 au, OR=2.58) changes in session RPE workload were significantly related to increased non-contact soft tissue injury risk when compared with reference groups of <1250 au, <2000 au, and <250 au respectively. Moreover, during a pre-season training block, 3-weekly total distance covered (OR=5.49, p=0.008) and 3-weekly sprint distance (OR=3.67, p=0.074) were associated with a higher non-contact soft tissue injury risk [24]. While these studies compared injury risk with either absolute workload (e.g. 1-week, or 3-week), or previous-to-current week changes in workload, no study has investigated the comparison of acute and chronic running workloads in AF. In elite cricket fast bowlers, Hulin et al. [14] reported that large increases in acute bowling workload (i.e. balls bowled), represented by a high acute:chronic workload ratio, were associated with an increased risk of injury in the week following exposure. Further, in a cohort of elite rugby league players, a very-high acute:chronic workload ratio (≥2.11) for total distance, measured via GPS technology demonstrated the greatest risk of injury in the current (16.7% risk of injury) and subsequent (11.8% risk of injury) week [17]. Therefore, it is important to consider the delayed effect of the previous weeks’ workload when analysing workload-injury relationships.
To date, there is limited research that has investigated the relationship between acute and chronic running workloads and the acute:chronic workload ratio in elite Australian footballers. Therefore, the aim of the present study was to investigate if acute and chronic running workloads, and the acute:chronic workload ratio were associated with subsequent injury risk in elite Australian footballers.

3.3 Methods

3.3.1 Participants

Fifty-nine elite Australian football players from one club (mean±SD age, 23±4 years; height, 189±7 cm; mass, 88±8 kg) participated in this study. Data were collected over the course of two Australian Football League (AFL) seasons. Of the two seasons, 33 (56%) participants competed in both seasons and 26 (44%) competed in one season – equating to a total of 92 individual seasons. Each season consisted of a 16-week pre-season period including running and football-based sessions, followed by a 23-week in-season period. All experimental procedures were approved by The Australian Catholic University Human Research Ethics Committee.

3.3.2 Training and Competition Loads

Workload data were collected via GPS technology, which provided information on the training and match workloads of players. The GPS units sampled at 10 Hz (Optimeye S5, Catapult Innovations, Melbourne, Victoria, Australia) and also housed a tri-axial accelerometer, gyroscope, and magnetometer sampling at 100 Hz. Workload variables consisted of; (1) total distance (m), (2) low-speed distance (0.00–6.00 km.hr\(^{-1}\)), (3) moderate-speed distance (6.01–18.00 km.hr\(^{-1}\)), (4) high-speed distance (18.01–24.00 km.hr\(^{-1}\)), (5) very
high-speed distance (>24.00 km.hr\(^{-1}\)), and (6) player load (au). This technology has demonstrated adequate validity and reliability when measuring velocity, distance, acceleration, and player load [40, 67]. Player load was measured as a modified vector magnitude using accelerometer data from each vector (X, Y, and Z axis), and was expressed as a measure of ‘load’ on each player by detecting the rate of change in each vector [67]. Medical staff at the football club classified all injuries, with injury reports maintained and updated daily throughout the season. An injury was defined as any non-contact ‘time-loss’ injury obtained during training or competition that resulted in a missed training session or missed game [25].

3.3.3 Calculating the Acute:Chronic Workload Ratio

Data were categorised into weekly blocks from Monday through Sunday. One-week data represented acute workload, while a four-week average of acute workload represented chronic workload. The acute:chronic workload ratio was calculated by dividing the acute workload by the chronic workload [9, 14, 17]. Where the acute workload was greater than the chronic workload, a high acute:chronic workload ratio was calculated, and where the chronic workload was greater than the acute workload, a low acute:chronic workload ratio was calculated. A player who completed no external work (i.e. 0 meters run) would not have produced a workload, and therefore would not have produced a risk of injury for that week. These zero workload data were included in the analysis for the purpose of calculating chronic workload and exploring the risk of injury in the weeks following no work, although not considered in the week where no workload was performed. Similarly, the first three weeks of data in the pre-season were excluded only in the chronic workload category, until an accurate chronic workload could be calculated in the fourth week. In the event that a player
participated in modified or rehabilitation field training, all workload data were included in the analysis.

Data were categorised into discrete ranges for each variable based on the workload accumulated per week. Workload variables were divided into independent logical increments to enhance the real-world application of these data. These increments were the same when calculating acute and chronic workloads and injury likelihoods. The acute:chronic workload ratio was divided into the following ranges; (1) very low, ≤0.49, (2) low, 0.50–0.99, (3) moderate, 1.0–1.49, (4) high, 1.5–1.99, and (5) very high, ≥2.0 (Hulin et al., 2014). Injury likelihoods were calculated based on the total number of injuries sustained relative to the total number of exposures to each workload range. Injury likelihoods and relative risks (RR) were calculated for the present week, and subsequent week [136].

3.3.4 Statistical Analysis

Differences in workload between the pre-season period and in-season period were determined using a 1-way analysis of variance (ANOVA). The likelihood of sustaining an injury was analysed using a binary logistic regression model with significance set at p < 0.05. Acute workload, chronic workload, and acute:chronic workload ratio ranges were independently modelled as predictor variables, and injury/no injury as the dependent variable. The very high acute:chronic workload ratio (≥2.0) was used as the reference category for which each other category was compared. Given the practical nature of the study, magnitude-based statistics were used to determine any practically significant differences between groups [137, 138], along with 90% confidence intervals. Likelihoods were subsequently generated and thresholds used for assigning qualitative terms to chances were as follows: <1%, almost
certainly not; <5%, very unlikely; <25%, unlikely; <50%, possibly not; ≥50%, possibly; ≥75%, likely; ≥95%, very likely; ≥99%, almost certainly [137, 138]. The magnitude of difference was considered practically significant when the likelihood was ≥75% [137, 138]. Prior to beginning our study, 40 players were contracted to the AFL squad. Given that on average 90% of players in an AFL club sustain a new injury in any given season [5], the calculated number of injuries required to achieve an alpha level of 0.05 with a confidence level of 90% was 34.

3.4 Results

Over the course of the study, 40 injuries were recorded, with 18 of these injuries sustained during the pre-season period. Of these, the hamstring (44%) and thigh (27%) were the most commonly injured sites. Similarly, of the 22 injuries recorded during the in-season period, hamstring injuries (59%) were the most common, followed by calf (18%) and thigh (9%) injuries.

Descriptive statistics for all participants’ external workload variables over the course of the study are shown in Table 2. Acute workloads were significantly (p<0.05) higher during the pre-season period for low, high, and very high-speed distance, and player load when compared with the in-season period. Similarly, chronic workloads were significantly (p<0.05) higher for high and very high-speed distance during the pre-season period. However, chronic workloads for total, low, and moderate-speed distance were significantly (p<0.05) higher during the in-season period. The acute:chronic workload ratio was significantly (p<0.05) higher for total, low-, moderate-, high-, and very high-speed distance, along with player load during the pre-season period when compared with the in-season period.
Table 2. Descriptive statistics for all participants’ external workload variables over the course of the study.

All data are mean ± SD. *Significantly (p<0.05) different from pre-season. ACWR = acute:chronic workload ratio. Data were calculated for all players from every main, modified, or rehabilitation session completed across the pre- and in-season period.

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<thead>
<tr>
<th>Workload Variable</th>
<th>Pre-Season</th>
<th>In-Season</th>
<th>Pre-Season vs. In-Season (p value)</th>
</tr>
</thead>
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<tr>
<td>Total distance (m)</td>
<td>17905.2 ± 7376.2</td>
<td>14353.9 ± 6204.8</td>
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<tr>
<td>Low-speed distance (m)</td>
<td>4837.0 ± 1897.8</td>
<td>3843.6 ± 1718.2</td>
<td>0.032</td>
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<tr>
<td>Moderate-speed distance (m)</td>
<td>9248.6 ± 4131.9</td>
<td>7372.0 ± 3375.8</td>
<td>0.042</td>
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<tr>
<td>High-speed distance (m)</td>
<td>3130.5 ± 1917.3</td>
<td>2584.6 ± 1359.7</td>
<td>0.001</td>
</tr>
<tr>
<td>Very high-speed distance (m)</td>
<td>902.3 ± 746.4</td>
<td>728.9 ± 491.2</td>
<td>0.001</td>
</tr>
<tr>
<td>Player load (au)</td>
<td>1696.13 ± 720.6</td>
<td>1360.4 ± 621.8</td>
<td>0.046</td>
</tr>
</tbody>
</table>

Note: W = any high-speed distance (m)  
H = high-speed distance (m)  
M = moderate-speed distance (m)  
L = low-speed distance (m)  

ACWR = acute:chronic workload ratio.
3.4.1 Current Week

The relationships between acute and chronic workloads and the risk of injury in the current week during the pre-season period are shown in Figure 1A,B respectively. No significant relationships (likelihood ≤75%, p>0.05) were observed between acute and chronic workloads and injury risk during the pre-season. During the in-season period in the current week, a total distance chronic workload of >20,000 m was associated with a lower risk of injury than a total distance chronic workload <5,000 m (Relative Risk [RR]=0.15 (90% CI 0.08 to 0.29); p=0.034; 98.1%, very likely) (Figure 2B). No other significant relationships were observed between acute and chronic workloads and injury risk in the current week during the season.

During the in-season period in the current week, players with an acute:chronic workload ratio of >2.0 for total distance were 5 to 8 times more likely to sustain an injury than players with an acute:chronic workload ratio of <0.49 (RR=7.98 (CI 5.86 to 10.88); p=0.015; 99.2%, almost certainly), and between 0.5-0.99 (RR=5.04 (CI 4.16 to 6.11); p=0.012; 99.3%, almost certainly) (Figure 2C). Furthermore, players with an acute:chronic workload ratio >2.0 for low-speed (RR=9.06 (CI 7.78 to 10.56); p=0.007; 99.6%, almost certainly) and moderate-speed distance (RR=10.98 (CI 10.73 to 11.25); p=0.002; 99.9%, almost certainly) had an increased likelihood of injury in comparison with players who recorded an acute:chronic workload ratio of 0.50-0.99 (Figure 2C). Similarly, an acute:chronic workload ratio of >2.0 for high-speed distance was associated with a 6 to 12 times greater injury risk than acute:chronic workload ratios of <0.49 (RR=11.62 (CI 10.04 to 13.45); p=0.006; 99.7%, almost certainly), 0.50-0.99 (RR=9.63 (CI 9.21 to 10.07); p=0.002; 99.9%, almost certainly), and 1.0-1.49 (RR=6.54 (CI 6.19 to 6.92); p=0.003; 99.8%, almost certainly). Players with a player load acute:chronic workload ratio of >2.0 had a greater risk of injury than players with
a player load acute:chronic workload ratio of 0.50-0.99 (RR=6.27 (CI 5.62 to 6.00); p=0.006; 99.7%, almost certainly) and 1.0-1.49 (RR=7.72 (CI 7.57 to 7.88); p=0.001; 99.9%, almost certainly) (Figure 2C). Collectively, these results demonstrate that a large spike in acute workload, resulting in a very high (>2.0) ACWR, during the in-season period is associated with a significant increase in injury risk during the current week.

3.4.2 Subsequent Week

During the subsequent week in the pre-season period, a high acute workload >20,000 m for total distance was associated with a decreased likelihood of injury (RR=0.27 (CI 0.17 to 0.41); p=0.033; 98.1%, very likely) when compared with a moderate acute workload of 10,000 – 15,000 m. No other significant relationships (likelihood ≤75%, p>0.05) were observed between acute workloads and injury risk in the subsequent week during the pre-season. The likelihood of injury for selected acute and chronic workload running variables in the subsequent week during the in-season period is shown in Figure 2D,E. Higher acute workloads for player load >2,500 au (RR=2.02 (CI 1.47 to 2.76); p=0.045; 97%, very likely) were coupled with an increased injury risk. A high chronic workload >20,000 m for total distance was associated with a lower injury risk (RR=0.20 (CI 0.01 to 3.02); p=0.167; 90.6%, likely) when compared with a low chronic workload <5,000 m. Similarly, a high chronic workload >6,000 m for low-speed distance was associated with a decreased likelihood of injury (RR=0.33 (CI 0.01 to 18.70), p=0.331, 80.9%, likely) when compared with a low chronic workload <2,000 m.

In the subsequent week during the pre-season period, an acute:chronic workload ratio of >2.0 had an increased likelihood of injury when compared with players with a lower acute:chronic
workload ratio for a number of variables. When compared with an acute:chronic workload ratio of >2.0, an acute:chronic workload ratio of 1.0-1.49 for total distance (RR=4.87 (CI 2.33-10.21); p=0.047; 97.3%, very likely), low-speed distance (RR=8.29 (CI 2.90 to 23.69); p=0.05; 97.3%, very likely), and player load (RR=12.46 (CI 8.35 to 18.59); p=0.016; 99.1%, almost certainly). Similarly, an acute:chronic workload ratio of >2.0 for high-speed distance compared with an acute:chronic workload ratio of 0.50-0.99 was associated with an increased likelihood of injury (RR=6.46 (CI 4.63 to 9.02); p=0.018; 99%, almost certainly) (Figure 1F).

During the in-season period, players with an acute:chronic workload ratio of >2.0 had an increased likelihood of injury when compared with players with a lower acute:chronic workload ratio. Specifically, when a player exceeded an acute:chronic workload ratio of 2.0, compared to 1.0-1.49, the likelihood of injury were increased 4- to 7-fold for total distance (RR=5.49 (CI 4.19 to 7.20); p=0.016; 99.1%, almost certainly), low-speed distance (RR=7.25 (CI 6.44 to 8.16); p=0.006; 99.7%, almost certainly), moderate-speed distance (RR=7.21 (CI 6.80-7.65); p=0.003; 99.8%, almost certainly), high-speed distance (RR=4.36 (CI 3.50 to 5.43); p=0.015; 99.1%, almost certainly), and player load (RR=5.80 (CI 4.62 to 7.27); p=0.013; 99.3%, almost certainly) (Figure 2F). Collectively, these findings suggest that a large spike in acute workload, resulting in a very high (>2.0) ACWR, during the in-season period was associated with a significant increase in injury risk during the subsequent week.
Figure 1. Likelihood of injury at acute (A) and chronic (B) external workloads, and acute:chronic workload ratio [ACWR] (C) for the current week, and acute (D) and chronic (E) external workloads, and acute:chronic workload ratio [ACWR] (F) for the subsequent week, during the pre-season period.

TD = Total distance; LSD = Low-speed distance; HSD = High-speed distance; PL = Player Load.
Figure 2. Likelihood of injury at acute (A) and chronic (B) external workloads, and acute:chronic workload ratio [ACWR] (C) for the current week, and acute (D) and chronic (E) external workloads, and acute:chronic workload ratio [ACWR] (F) for the subsequent week, during the in-season period.

TD = Total distance; LSD = Low-speed distance; HSD = High-speed distance; PL = Player Load.
3.5 Discussion

Based on previous research [11, 12, 14], this study determined the relationships between acute and chronic workloads, the acute:chronic workload ratio and injury risk in elite Australian Footballers. When chronic workload was greater than acute workload, resulting in a low acute:chronic workload ratio, a lower risk of injury was observed, while sharp spikes in acute workload relative to chronic workload (>2.0), were associated with greater injury risk during the in-season period. Similar to previous findings [14, 17], a very high acute:chronic workload ratio of greater than 2.0 resulted in up to an 8-fold increase in the risk of non-contact soft tissue injury in the week the workload was performed. Additionally, greater increases in acute workload relative to chronic workload during the in-season resulted in a significantly increased injury risk in the subsequent week to the workload being performed. Further, higher chronic workloads alone were associated with a lower injury risk in this cohort of players, suggesting that higher chronic workloads may offer a protective effect against injury. These findings demonstrate that 1) in elite Australian football players, sharp increases in workloads increase the likelihood of injury in both the week the workload is performed, and the subsequent week, and 2) both acute and chronic workload, and the acute:chronic workload ratio need to be modelled independently and relative to each other as a ratio to quantify injury risk.

A significant relationship between training workloads and injury during the pre-season period was found. Of these, an acute:chronic workload ratio of >2.0 for total distance resulted in a 5-fold increase in injury likelihood in the subsequent week when compared with an acute:chronic workload ratio of 1.0-1.49. Similarly, a high-speed running acute:chronic workload ratio of >2.0 was associated with a 6-fold increase in the likelihood of injury in the subsequent week. Further, during the in-season period, a positive relationship existed.
between players who recorded a very high acute:chronic workload ratio (>2.0), and increased injury likelihood. This suggests that players are not as well equipped to handle sharp spikes in workload in the current week during the season as they are during the pre-season period, possibly due to increased match and physical demands during competition along with a greater requirement for recovery [21, 139]. These findings highlight the need to increase workload progressively and systematically in order to reach high chronic workloads during both the pre- and in-season periods [140, 141].

The present study explored the relationship between acute and chronic workloads, along with the acute:chronic workload ratio for a range of workload variables. Our findings show similar trends between different running workload variables, accelerometer loads, and injury likelihood. That is, when compared with chronic workload, greater increases in acute workload, resulting in a high acute:chronic workload ratio (>2.0), were coupled with greater injury likelihoods for all workload variables. However, higher chronic workloads for total and high speed distance were associated with a decreased risk of injury, which suggests that high chronic workloads over a 4-week period may result in positive physical adaptations [9, 11, 12, 14, 17], which possibly protect against non-contact, soft-tissue injury. With the continued advancement and use of monitoring technology, these novel findings provide information for strength and conditioning staff to monitor a range of acute and chronic workload variables and acute:chronic workload ratios to examine individual player’s workloads and their injury risk.
3.5.1 Limitations

While the use of this performance model [11, 12] is novel, there are some limitations that warrant discussion. First, because weekly blocks were categorised from Monday to Sunday, it is possible that a player sustained an injury early in the week, and subsequently recorded a lower external workload in the current week. Second, our results may have been influenced by a small sample size recorded at extremities of the acute:chronic workload ratio (i.e. >2.0). This may be due to load monitoring systems established by the football club to minimise the number of players reaching this very high acute:chronic workload ratio. Moreover, it should be noted that the ability to draw conclusions from this study is limited due to the small number of non-contact ‘time-loss’ injury events. The exclusion of contact injuries decreased the overall injury count, although we rationalized that an assessment of the relationship between running workloads and contact injury risk may be difficult to justify in AF. Clearly, a larger study involving more players across a larger number of teams would strengthen the present findings. Further, the use of individualised speed thresholds as opposed to absolute speed thresholds currently used may provide an enhanced understanding of player workloads and consequently injury risk. Finally, it should be noted that no measures of internal workload or strength training were included in this study. It has been previously shown that well-developed strength and power may assist to reduce the risk of contact injury in professional rugby league players [142]. Our finding of large acute spikes in external workload contributing to injury risk has implications for subsequent training. If a player is injured due to spikes in workload, it may reduce his opportunity to develop strength, which in turn may further increase his risk of injury. Therefore, the importance of identifying large acute spikes in external workload cannot be overstated. Extending upon the present study by incorporating internal workloads, including individualised speed thresholds, and exploring...
optimal external workload thresholds for players to minimise the risk of injury would be beneficial for coaches and strength and conditioning staff.

3.6 Conclusion

In conclusion, we investigated the relationship between acute and chronic external running workloads, the acute:chronic workload ratio, and injury risk in elite Australian football players. By applying a previously used model that takes into account current workload, and the workload that the athlete has been prepared for [11, 12, 14, 17], we aimed to extend on previous work which has examined the relationship between workload and injury in elite AF players [24, 25]. The results of this study demonstrate that abrupt increases in acute workload are significantly related to injury in both the current and subsequent week during the in-season period. Furthermore, it appears that high chronic workloads for total distance and low-speed distance offer a protective effect, reducing the likelihood of injury. These findings highlight the importance of individual monitoring of both acute and chronic workloads, and the acute:chronic workload ratio in order to reduce the risk of injury in elite Australian football players. In light of the present and previous findings [14, 17], the acute:chronic workload ratio is a novel model to quantify the load an athlete has performed in the current week relative to what they have been prepared for over the past 4 weeks. Moreover, the acute:chronic workload ratio can be applied across a range of sports (i.e. football, rugby, cricket).
3.7 Acknowledgements

The authors extend their thanks to the players and staff of the Brisbane Lions Football Club for their support and contribution to this study. No external financial support was provided for this project.
Chapter 4

Study 2 – Relationship between pre-season training load and in-season availability in elite Australian Football players

This study has been accepted for publication following peer review. Full reference details are:

4.1 Abstract

Objectives: Investigate the relationship between the proportion of pre-season training sessions completed, and load and injury during the ensuing Australian Football League season.

Design: Single cohort, observational study.

Methods: Forty-six elite male Australian football players from one club participated in this study. Players were divided into three equal groups based on the amount of pre-season training completed (high, HTL, > 85% sessions completed; medium, MTL, 50–85% sessions completed; and low, LTL, < 50% sessions completed). Global Positioning System (GPS) technology was used to record training and game loads, with all injuries recorded and classified by club medical staff. Differences between groups were analysed using a two-way (group x training/competition phase) repeated measures ANOVA, along with magnitude-based inferences. Injury incidence was expressed as injuries per 1,000 hours.

Results: The HTL and MTL group completed a greater proportion of in-season training sessions (81.1% and 74.2%) and matches (76.7% and 76.1%) than the LTL (56.9% and 52.7%) group. Total distance and Player Load were significantly greater during the first half of the in-season period for the HTL (p = 0.03, ES = 0.88) and MTL (p = 0.02, ES = 0.93) groups than the LTL group. The relative risk of injury for the LTL group (26.8/1,000 hours) was 1.9 times greater than the HTL group (14.2/1,000 hours) ($\chi^2 = 3.48$, df = 2, p = 0.17).

Conclusions: Completing a greater proportion of pre-season training resulted in higher training loads and greater participation in training and competition during the competitive phase of the season.
4.2 Introduction

During Australian football (AF) match-play, players are required to perform repeated high-speed (i.e. sprinting, running) efforts and physical contacts, interspersed with low-speed (i.e. jogging, walking) movements [28, 31]. In order to reach and maintain the required level of physical activity throughout a match, strength and conditioning staff are required to prescribe adequate training loads to enhance physical qualities, while also minimising the negative responses to training (e.g. fatigue, illness, and injury) [97, 143]. As previously suggested [101], an inadequate training stimulus will fail to elicit the required physiological adaptation, while an excessive training stimulus, with inadequate recovery periods may increase the risk of injury or illness.

During the competitive season, it is difficult to prescribe a training stimulus sufficient to enhance fitness, as time to allow recovery between matches is required [144]. Accordingly, the pre-season period is seen as a crucial period to develop physical qualities to meet the required level of physical demands during match-play [97]. Previously, training loads during the pre-season period have been reported as 2–4 times greater than during the in-season period [145, 146], and consequently the accurate control of training loads during this period is essential to both maximise positive training adaptations, and minimise the negative training response [145-147]. The relationship between training load and incidence of injury and illness over a pre-season period has been analysed, with Piggott et al. [96] reporting no significant relationships between injuries or illness and training load across this period. However these findings should be interpreted with some caution due to the small number of injuries (n = 5) and study duration (a 15–week pre-season). Further research and larger studies are required to provide a more comprehensive understanding of the relationship
between load and injury during the pre-season period, and the ensuing in-season period, including early season and late season.

The physical demands of AF have increased over the last decade [64], and soft tissue injuries remain the most common injury in the game [6]. Previously, it has been shown that high training loads, or inadequate recovery periods can increase the risk of soft tissue injury in elite team sport athletes [102, 103]. As such, an increased emphasis has been placed on quantifying loads during training and competition, to determine the relationship between load and injury [24, 25, 103]. Specifically, in sub-elite rugby league players, increases in session-RPE training load have been associated with increases in the likelihood of injury [101]. In addition, recent work by Rogalski et al. [25] in AF showed that larger 1-weekly (>1750 arbitrary units, OR = 2.44–3.38), 2-weekly (>4000 arbitrary units, OR = 4.74), and previous-to-current week changes in load (>1250 arbitrary units, OR = 2.58) were significantly related to an increased injury risk during the in-season period. Similarly, during a pre-season training block, greater 3-weekly distance covered (OR = 5.49, p = 0.008) and 3-weekly sprint distance (OR = 3.67, p = 0.074) were associated with a higher non-contact soft tissue injury risk during the pre-season period [24].

Recent investigations into the relationship between load and injury, and load and performance have investigated the acute:chronic load ratio, i.e. the load performed in 1 week (acute load) relative to the average of the previous four weeks (chronic load) [9, 16, 17]. Specifically, in elite cricket fast bowlers, it has been shown that high loads over a chronic period (i.e. 4-weeks) results in positive physiological adaptations that potentially minimise the fatigue response, and in turn reduce the likelihood of injury [14]. Similarly, Hulin et al.
reported that elite rugby league players with a high chronic load, compared to those with a low chronic load, were more resistant to injury when acute load was similar to chronic load (i.e. acute:chronic load ratio ~0.8–1.3) [17]. Collectively, these findings suggest that high chronic loads, coupled with moderate acute:chronic load ratios may provide a protective effect against injury [9, 16, 17].

Recent work from elite rugby league has shown that players who completed a greater proportion of the planned pre-season experienced a lower incidence and severity of injuries during the competitive phase of the season [15]. While studies have explored the relationship between load and injury in elite AF players, there is limited research that has investigated the relationship between the proportion of pre-season training sessions completed, and subsequent training and match loads and injury risk in the ensuing season. Therefore, it was the aim of the present study to investigate the relationship between the proportion of pre-season training completed and subsequent in-season load, match availability, and injury risk in the ensuing season in elite Australian football players.

4.3 Methods
4.3.1 Participants

Forty-six elite Australian football players from one professional Australian Football League (AFL) club (mean ± SD age, 23.1 ± 3.7 years; height, 189.2 ± 7.1 cm; mass, 87.0 ± 8.2 kg) participated in this study. All participants received a clear explanation of the study, including information on the risks and benefits of participation. The Australian Catholic University Human Research Ethics Committee approved all experimental procedures (Approval Number 182E).
4.3.2 Training and Competition Loads

Participants were fitted with a 10 Hz GPS (Global Positioning System) unit (Optimeye S5, Catapult Innovations, Melbourne, Victoria, Australia) during data collection. The GPS unit also housed a tri-axial accelerometer, gyroscope, and magnetometer sampling at 100 Hz to provide information on the movement demands during training and competition. Participants were equally divided into thirds and assigned to a high (HTL, completed >85% of pre-season sessions, n = 15), medium (MTL, completed 50–84.9% of pre-season sessions, n = 16), or low (LTL, completed <50% of pre-season sessions, n = 15) training load group at the beginning of the competitive season based on the percentage of main pre-season sessions completed. The characteristics of players in each group were as follows; HTL group (mean ± SD age, 22.8 ± 2.9 years; playing experience, 3.9 ± 2.6 years; percentage of pre-season spent in rehabilitation group, 4.6 ± 4.3%), MTL group (mean ± SD age, 23.3 ± 3.8 years; playing experience, 5.0 ± 3.5 years; percentage of pre-season spent in rehabilitation group, 21.8 ± 11.5%), LTL group (mean ± SD age, 22.8 ± 4.2 years; playing experience, 4.7 ± 4.3 years; percentage of pre-season spent in rehabilitation group, 46.0 ± 33.5%). While it would have been ideal for all players to complete all training sessions, on occasions, players were required to undertake modified training activities in order to minimise excessive fatigue and injury risk. The types of training sessions were main training sessions, modified training sessions, and rehabilitation training sessions. Main training sessions reflected completion of the total prescribed sessions comprised of running and speed along with skills; modified training sessions reflected partial completion of prescribed sessions; and rehabilitation sessions reflected completion of an individualised injury-specific return-to-play program.
Training and match loads were categorised cumulatively into the following variables; (1) total distance (TD, m), (2) low-speed distance (LSD, 0.00–6.00 km.hr⁻¹), (3) moderate-speed distance (MSD, 6.01–18.00 km.hr⁻¹), (4) high-speed distance (HSD, 18.01–24.00 km.hr⁻¹), (5) very high-speed distance (VHSD, >24.00 km.hr⁻¹), and (6) player load (PL, au). This technology has demonstrated adequate validity and reliability for accurate measurement of velocity distance, acceleration, and player load [40, 67]. Player load was measured as a modified vector magnitude using accelerometer data from the microtechnology unit. It is expressed as the square root of the sum of the squared instantaneous rate of change in acceleration in each of the three vectors (X, Y, and Z axis) and divided by 100 [67]. In addition, all injuries were classified by medical staff at the football club with injury reports maintained and updated daily throughout the season. An injury was recorded if it occurred during training or competition and resulted in a missed match [25]. Injuries were categorised according to injury type (description) and body site (location).

### 4.3.3 Statistical Analysis

Data were analysed using SPSS 22.0 (SPSS Inc., Chicago IL, USA), where load variables in: 1) the pre- and in-season period, and 2) the first and second half of the in-season period were compared using a two-way (load group x training/competition phase) repeated measures ANOVA. If significant main effects were found, Bonferroni post hoc analyses were used to determine the source/s of the differences. Data were checked for normality using a Shapiro-Wilk test, and a Pearson’s product moment correlation coefficient was used to assess the relationships among: percentage of pre-season completed, match availability, pre-season training load, and in-season training load. Descriptors were used to describe the size of the correlation between variables, and were as follows: trivial; < 0.1, small; 0.1–0.3, moderate;
0.3–0.5, large; 0.5–0.7, and nearly perfect; > 0.9 [138]. Given the practical nature of the study, magnitude-based statistics were used to determine any practically meaningful differences between groups [137, 138]. The magnitude of the change in the dependent variables were also assessed using Cohen’s effect size (ES) statistic [148], and 90% confidence intervals (CI). Effect sizes of < 0.2, 0.2–0.6, 0.61–1.2, 1.21–2.0, and > 2.0 were considered trivial, small, moderate, large, and very large, respectively [138]. Likelihoods were subsequently generated and thresholds used for assigning qualitative terms to chances were as follows: < 1%, almost certainly not; < 5%, very unlikely; < 25%, unlikely; < 50%, possibly not; ≥ 50%, possibly; ≥ 75%, likely; ≥ 95%, very likely; ≥ 99%, almost certainly [137, 138]. The magnitude of differences between groups was considered practically meaningful when the likelihood was ≥ 75% [137, 138]. In addition, injury rates were also calculated for each load group (i.e. high, medium, and low). Injury incidence was calculated by dividing the total number of injuries by the overall exposure hours for each load group and expressed as rates per 1,000 hours of exposure and 95% confidence intervals (CIs). The chi squared test (χ²) was used to determine significant differences between load groups. All data were reported as means ± SD and significance was set at p < 0.05.

4.4 Results

Across the season, a total of 3,710 individual sessions were recorded. Of these, 1,765 individual training sessions were observed during the pre-season period, and 1,945 individual sessions (i.e. training and competition) were recorded during the in-season period. Collectively, training loads were ~1.3 times greater during the pre-season period than the in-season period (p = 0.02). Figure 3 shows the total training duration and the proportion of sessions distribution across the pre- (A, B) and in-season (C, D) periods. During the pre-season period, the HTL group collectively completed 87.2% of the prescribed sessions, while
the MTL and LTL groups completed 61.3% and 35.4%, respectively. Similarly, during the in-season period, the proportion of time in main training was slightly higher for the HTL group with 57.3%, compared with the MTL groups with 57.1% (p > 0.05, ES=0.16 [-0.51–0.66], 52% Possibly). Further, the proportion of time in main training for both the HTL (p > 0.05, ES=1.20 [0.71–1.70], 100% Almost Certainly) and the MTL (p > 0.05, ES=1.01 [0.47–1.56], 99% Almost Certainly) groups were higher than the LTL (49.8%) group. Similarly, the HTL and MTL groups were available to play for 76.7% and 76.1% of in-season competitive matches, respectively (p > 0.05, ES=0.02 [-0.64–0.60], 41% Possibly). In comparison to the HTL (p > 0.05, ES=0.84 [0.27–1.41], 97% Very Likely) and MTL (p > 0.05, ES=0.82 [0.25–1.39], 96% Very Likely) groups, the LTL group was only available to play for 52.7% of in-season competitive matches.
Figure 3. Total duration of training hours during the pre- (A) and in-season (C) periods, with proportion of sessions completed for each load group (i.e. high, medium, and low) during the pre- (B), and in-season (D) period.
During the pre-season period, the HTL group completed greater training load for all variables than both the MTL (p < 0.05, ES=1.32–1.58, 100% Almost Certainly) and LTL (p < 0.05, ES=1.47–1.78, 100% Almost Certainly) groups (Table 3). Similarly, the MTL group completed greater training load for each measured variable (p < 0.05, ES=1.09–1.43, 100% Almost Certainly) than the LTL group. During the competitive season, there were no statistically significant differences in TD covered between the groups, however practically meaningful differences were observed where the HTL (p=0.12, ES=0.72 [0.13–1.31], 93% Likely) and MTL (p=0.12, ES=0.73 [0.16–1.31], 94% Likely) groups covered practically greater TD than the LTL group. Moreover, the HTL group completed moderately greater VHSD (p=0.01, ES=0.80 [0.22–1.38], 96% Very Likely) and PL (p=0.12, ES=0.73 [0.14–1.31], 93% Likely) than the LTL group. The MTL group had moderately greater VHSD (p=0.01, ES=0.54 [0.05–1.14], 83% Likely), and PL (p=0.15, ES=0.70 [0.12–1.28], 92% Likely) than the LTL group. There were no differences between the HTL and MTL groups during the season.
### Table 3.
Quantification of weekly training and game loads throughout the pre- and in-season period for each load group (i.e., high, medium, and low).

<table>
<thead>
<tr>
<th>Variables</th>
<th>Pre-Season</th>
<th>In-Season</th>
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<tbody>
<tr>
<td>Player load (au)</td>
<td>1900 ± 670</td>
<td>1538 ± 733</td>
</tr>
<tr>
<td>Very high-speed distance (m)</td>
<td>1000 ± 670</td>
<td>1538 ± 733</td>
</tr>
<tr>
<td>High-speed distance (m)</td>
<td>1048 ± 744</td>
<td>1538 ± 733</td>
</tr>
<tr>
<td>Moderate-speed distance (m)</td>
<td>4560 ± 2306</td>
<td>1048 ± 744</td>
</tr>
<tr>
<td>Low-speed distance (m)</td>
<td>3709 ± 2296</td>
<td>4560 ± 2306</td>
</tr>
<tr>
<td>Total distance (m)</td>
<td>17897 ± 3564</td>
<td>3709 ± 2296</td>
</tr>
</tbody>
</table>

All data are mean ± SD. *Denotes significantly different from low group. †Denotes significantly different from medium group. **Denotes practically meaningful difference from medium group. ***Denotes practically meaningful difference from low group.
Percentage of pre-season training completed, match availability, pre-season training load, and in-season training load are shown in Table 4. A near perfect correlation was observed between the percentage of pre-season training completed and pre-season TD (r = 0.96, p = 0.001). Further, a very large correlation was observed between the percentage of pre-season training completed and pre-season HSD (r = 0.86, p = 0.001). Similarly, a near perfect correlation was observed between in-season TD and match availability (r = 0.95, p = 0.01). There were moderate correlations observed between percentage of pre-season training completed and match availability (r = 0.31, p = 0.04), and pre-season TD (r = 0.36, p = 0.02), HSD (r = 0.34, p = 0.02), and match availability.
Table 4. Relationships among the percentage of pre-season completed, match availability, pre-season training load, and in-season training load.

<table>
<thead>
<tr>
<th>Variables</th>
<th>% Pre-season complete</th>
<th>Pre-season TD</th>
<th>Pre-season HSD</th>
<th>Pre-season VHSD</th>
<th>In-season TD</th>
<th>In-season HSD</th>
<th>In-season VHSD</th>
<th>Match availability</th>
<th>% Pre-season completed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Match availability</td>
<td>1.00</td>
<td>0.33</td>
<td>0.62</td>
<td>0.95</td>
<td>0.28</td>
<td>0.34</td>
<td>0.36</td>
<td>0.31</td>
<td>0.31</td>
</tr>
<tr>
<td>Pre-season TD</td>
<td>0.96*</td>
<td>1.00</td>
<td>0.95*</td>
<td>0.74*</td>
<td>0.30*</td>
<td>0.26*</td>
<td>0.29*</td>
<td>0.36*</td>
<td>0.36*</td>
</tr>
<tr>
<td>Pre-season HSD</td>
<td>0.86*</td>
<td>0.95*</td>
<td>1.00</td>
<td>0.80*</td>
<td>0.30*</td>
<td>0.36*</td>
<td>0.53*</td>
<td>0.62*</td>
<td>0.53*</td>
</tr>
<tr>
<td>Pre-season VHSD</td>
<td>0.69*</td>
<td>0.74*</td>
<td>0.80*</td>
<td>1.00</td>
<td>0.30*</td>
<td>0.44*</td>
<td>0.53*</td>
<td>0.62*</td>
<td>0.53*</td>
</tr>
<tr>
<td>In-season TD</td>
<td>0.24</td>
<td>0.30*</td>
<td>0.30</td>
<td>0.30</td>
<td>1.00</td>
<td>0.75*</td>
<td>0.60*</td>
<td>0.95*</td>
<td>0.95*</td>
</tr>
<tr>
<td>In-season HSD</td>
<td>0.13</td>
<td>0.23</td>
<td>0.36*</td>
<td>0.44*</td>
<td>0.75*</td>
<td>1.00</td>
<td>0.80*</td>
<td>0.62*</td>
<td>0.62*</td>
</tr>
<tr>
<td>In-season VHSD</td>
<td>0.21</td>
<td>0.29</td>
<td>0.34*</td>
<td>0.53*</td>
<td>0.60*</td>
<td>0.80*</td>
<td>1.00</td>
<td>0.53*</td>
<td>0.53*</td>
</tr>
<tr>
<td>Match availability</td>
<td>0.31*</td>
<td>0.36*</td>
<td>0.34*</td>
<td>0.28</td>
<td>0.95*</td>
<td>0.62*</td>
<td>0.53*</td>
<td>1.00*</td>
<td>1.00*</td>
</tr>
</tbody>
</table>

Denotes a significant correlation (p < 0.05). TD = Total distance. HSD = High-speed distance. VHSD = Very high-speed distance.
During the first half of the season, the HTL (p=0.03, ES=0.88 [0.31–1.44], 97% Very Likely) and MTL (p=0.02, ES=0.93 [0.38–1.47], 98% Very Likely) groups covered significantly greater weekly TD than the LTL group. Similarly, PL values were significantly higher for both the HTL (p=0.03, ES=0.89 [0.33–1.45], 98% Very Likely) and MTL (p=0.02, ES=0.93 [0.38–1.48], 98% Very Likely) groups compared to the LTL group. The HTL group completed moderately greater (albeit not significantly) MSD (p=0.32, ES=0.60 [0.00–1.19], 87% Likely) and VHSD (p=0.18, ES=0.75 [0.17–1.34], 94% Likely) than the LTL group (Figure 4). Further, there were no significant or practical differences in any load category for the LTL group from the first to the second half of the season.
Figure 4. Quantification of weekly training and game loads (i.e. total loads) throughout the first and second half of the in-season period for each load group (i.e. high, medium, and low).

* Denotes a significant difference (p < 0.05) between early and late season. † denotes a practically meaningful difference (likelihood ≥ 75%) between early and late season.
Across the in-season period, 50 injuries were recorded, with the knee (22%), hamstring (14%), and ankle (10%) the most common sites of injury. Although there was a trend toward greater injury rates in the low load group, no significant differences ($\chi^2=3.48$, df=2, $p=0.17$) were found between the HTL (14.2 [95% CI, 6.92–25.50] per 1,000 hours), MTL (17.7 [95% CI, 9.90–27.22] per 1,000 hours), and LTL (26.8 [95% CI, 12.22–30.89] per 1,000 hours) groups.

4.5 Discussion

This study investigated the relationship between training load completed during the pre-season period and subsequent in-season weekly loads (i.e. training and match loads) and injury during the ensuing season in elite Australian football players. During the in-season period, the HTL group completed a greater proportion of main training sessions and matches than both the MTL and LTL groups. Similarly, there were large differences in the proportion of main training sessions completed and training load between the HTL, MTL, and LTL groups during the pre-season period. No differences between the HTL and MTL groups during the in-season were observed, however both groups were higher than the LTL group for TD, VHSD, and PL. In addition, there were moderate to large differences for TD, PL, MSD, and HSD between the HTL and MTL groups, and the LTL group during the first half of the season. Further, the lowest and highest injury rates were observed for the HTL and LTL groups, respectively.

Similar to previous findings [25, 146], training load was higher during the pre-season phase than the in-season phase. Further, very large to nearly perfect correlations existed among the percentage of pre-season training completed and pre-season TD and HSD. A moderate
correlation existed between the proportion of pre-season training completed and match availability suggesting that factors in addition to, or other than pre-season training determine in-season match availability. However, our findings demonstrate that 1) completing a greater proportion of pre-season training sessions results in a greater pre-season training load, 2) greater pre-season training load is positively associated with a greater in-season training load, and 3) greater in-season training load is positively associated with greater match availability.

Unlike previous work, once separated into respective load groups, training load was significantly higher during the pre-season phase for both the HTL and MTL groups, but not the LTL group. This is likely due to the fact that during the pre-season period, the LTL group were unable to complete as much training as both the HTL and MTL group, respectively (Figure 1A). These findings suggest that players in both the HTL and MTL groups had greater opportunity to 1) participate in a greater proportion of training and 2) maintain a higher training load to develop the required physical qualities to compete in matches during the in-season phase [97]. Of the training the LTL group did perform, they were only able to complete 35.4% of the prescribed training sessions. In contrast, the HTL group and the MTL group completed 87.2% and 61.3% of the prescribed training sessions, respectively (Figure 1B). This may be due to a multitude of factors including but not limited to; injury, “off-legs” conditioning, increased time spent in the rehabilitation program, and individually modified training load programs. Moreover, during the in-season period, players in the HTL and MTL groups spent more time completing main training sessions, and less time completing rehabilitation sessions than players in the LTL group (Figure 1C). Similar to previous findings [149], approximately 50% of external load was obtained through competition during the in-season period (Figure 1D). These findings have important practical applications for strength and conditioning staff involved in the preparation of athletes. Specifically, players
should attempt to complete as much of the planned pre-season training program as possible in order to; 1) develop the physical qualities required to compete in competition, and 2) develop resilience to tolerate training and match loads during the season [15].

As expected, there were significant differences among load groups for all measured load variables during the pre-season period. During the in-season there were no notable differences between the HTL and MTL groups, although both groups were higher than the LTL group for TD, VHSD, and PL. In addition, during the first half of the season TD and PL were significantly greater for the HTL and MTL groups compared to the LTL group. A possible explanation for this finding is that players who were unable to complete a large amount of pre-season training (< 50%) may have been underprepared for the physical demands of competition [28, 31], and therefore below the load threshold necessary to promote physiological adaptation [97]. As a consequence, their risk of injury may have increased due to an inadequate level of fitness [91, 97, 142]. In contrast, there were only moderate differences between both the HTL and MTL group and LTL for VHSD, with no significant differences between any groups during the second half of the season. This most likely reflects decreases in training load for the HTL and MTL groups due to an increased in-season focus on recovery between competitive matches [146, 150], as opposed to increases in training load for the LTL group. However, across the first to second half of the season, the LTL group experienced a minor increase (albeit not significant) in total load. With competition cited as the main external stimulus during an in-season weekly cycle [149], a possible explanation for this finding is that players within the LTL group were able to use competition to increase their weekly total load during the in-season period.
Recent investigations in cricket [14], and rugby league [17], have demonstrated that sustained high chronic loads may offer a protective effect against injury [9]. There were no significant differences between groups for injury rates, although injury rates were nearly two-fold greater in the LTL group compared with the HTL group. While these are preliminary findings from one club in an elite Australian football competition, further research is required to understand the protective effect of sustained high chronic load in Australian football.

While this study provides some novel findings surrounding training load, there are some limitations that warrant discussion. First, it should be acknowledged that the present data is from one club and may be solely related to this particular cohort of players in this particular season. It is also possible that the results are a reflection of the training philosophies of the coaches and strength and conditioning staff of the studied club, and may not reflect the training practices of other AFL clubs. Second, it should be noted that the ability to draw strong conclusions on the relationship between load and injury may be limited due to an overall low number of injuries (n = 50). Further investigations across a larger number of players and Australian football teams would clearly strengthen the present findings. Finally, no measures of internal load were included in this study. While GPS technology provides detailed information on the external load of players, other measures of internal training load (i.e. session-RPE, heart rate, etc.) should also be monitored to provide detailed insight into the training loads, and subsequent load-injury relationship of athletes. Including internal loads, larger injury numbers, and more players would provide a greater understanding of the relationship between load and injury.

4.6 Practical Applications

Nick Murray
Load and Injury in AFL
The results of the present study demonstrate that high training loads during the pre-season period allow players to develop the required physical qualities for competition, while also resulting in greater training and competition participation in-season. Further, greater pre-season participation may reduce the risk of injury in the ensuing in-season competition period. Similarly, players who complete less pre-season training, also complete less training and compete in fewer matches during the following season. These findings hold important ramifications for practitioners involved in the physical development and preparation of players. Particularly, there is a need to develop strategies to maximise participation in pre-season training as this may result in a greater proportion of the squad available for training and selection during the competitive phase of the season.

4.7 Conclusions

This is the first study to examine the relationship between the amount of pre-season training completed and subsequent training load and injury during the ensuing competitive season in elite Australian football players. Our findings demonstrate that players who are able to complete a greater amount of pre-season training are able to maintain higher training loads during the ensuing season, and similarly, players who complete less pre-season training also complete less training and fewer competitive matches during the in-season phase.

4.8 Acknowledgements

The authors would like to thank the players of the Brisbane Lions Australian Football Club for participating in and supporting this study.
Chapter 5

Study 3 – Calculating acute:chronic workload ratios using exponentially weighted moving averages provides a more sensitive indicator of injury likelihood than rolling averages

This study has been accepted for publication following peer review. Full reference details are:

5.1 Abstract

**Objective:** To determine if any differences exist between the rolling averages, and exponentially weighted moving averages (EWMA) models of acute:chronic workload ratio (ACWR) calculation and subsequent injury risk.

**Methods:** A cohort of 59 elite Australian football players from one club participated in this 2-year study. Global positioning system (GPS) technology was used to quantify external workloads of players, and non-contact “time-loss” injuries were recorded. The acute:chronic workload ratio were calculated for a range of variables using two models: (1) rolling averages, and (2) EWMA. Logistic regression models were used to assess both the likelihood of sustaining an injury, and the difference in injury likelihood between models.

**Results:** There were significant differences in the ACWR values between models for moderate (ACWR 1.0-1.49; p=0.021), high (ACWR 1.50-1.99; p=0.012), and very high (ACWR >2.0; p = 0.001) ACWR ranges. Although both models demonstrated significant (p<0.05) associations between a very high ACWR (i.e. >2.0) and an increase in injury risk for total distance ([Relative Risk, RR]=6.52–21.28) and high-speed distance (RR=5.87–13.43), the EWMA model was more sensitive for detecting this increased risk. The variance (R²) in injury explained by each ACWR model was significantly (p<0.05) greater using the EWMA model.

**Conclusions:** These findings demonstrate that large spikes in workload associated with an increased injury risk using both models, although the exponentially weighted moving averages model is more sensitive to detect increases in injury risk with higher acute:chronic workload ratios.
5.2 Introduction

The acute:chronic workload ratio (ACWR) is a model that provides an index of athlete preparedness. It takes into account the current workload (i.e. acute; rolling 7-day workload), and the workload that an athlete has been prepared for (i.e. chronic; rolling 28-day workload) [9, 14, 151]. Based on early research by Banister et al. [11, 12] the ACWR is likened to the fitness-fatigue model, where the chronic load is analogous to a state of ‘fitness’ and the acute load is analogous to a state of ‘fatigue’ [9, 14]. If performance represents the difference between fitness and fatigue, the ACWR aims to predict performance by comparing acute and chronic loads as a ratio [11, 12, 14]. Further, the ACWR has been used to quantify injury likelihood, where very high ACWR ranges were associated with a significantly increased risk of injury [9, 14, 151].

The original work by Hulin et al. [14] aimed to determine whether acute and chronic workload, and the ACWR were associated with injury risk in elite cricket fast bowlers. They reported that large increases in acute bowling workload (i.e. balls bowled), represented by a high ACWR, were associated with an increased risk of injury in the week following exposure (Relative Risk [RR]=2.1 (CI 1.81 to 2.44), p=0.01). In addition, a high ACWR for internal workload (measured via session-RPE) was associated with an increased risk of injury in the subsequent week (RR=2.2 (CI 1.91 to 2.52), p=0.009). Further work across a range of sports [133], specifically elite rugby league [16, 17], Australian football (AF) [151], Gaelic football [27, 108], and soccer [111] has continued to examine the relationship between the ACWR and injury likelihood. The common theme of findings from these studies is that (1) sharp increases or ‘spikes’ in acute workload, resulting in a high ACWR are significantly related to injury in both the week the workload is performed and the subsequent week [152], and (2) higher chronic workloads may offer a protective effect against injury [152, 153].

Nick Murray
Load and Injury in AFL
A recent *BJSM* editorial [154] has raised concerns surrounding the use of rolling averages to assess workload, citing that they do not consider the timeframe in which a given stimulus occurred, nor the decaying nature of fitness and fatigue effects over time [154, 155]. While this may be the case, the ACWR model is evidence-based [9, 156] and is considered a best-practice approach for modelling the relationship between load and injury across a range of sports [135]. It is hypothesised that a non-linear training load model may be better suited to quantify injury risk [154], however there is currently no evidence that this type of model is superior to the current ACWR model [135].

Recently, Williams et al. [134] proposed the use of ‘exponentially weighted moving averages (EWMA)’ [157] as a new method to calculate acute and chronic load to address the decaying nature of fitness and fatigue. This method assigns a decreasing weighting to each older load value, thereby giving more weighting to the recent load undertaken by the athlete. This method differs to the current model of acute and chronic load calculation, where a rolling average considers a training session carried out the day before the analysis and a session occurring four weeks before as equal [154]. It is suggested that the EWMA approach may be better suited to calculate the ACWR and model load and injury relationships than the current rolling averages method [134].

To date, no research has investigated the difference between the previously established rolling average ACWR model, and the newly proposed EWMA model. Therefore, the aim of the present study was to investigate if any differences existed between the rolling average,
and EWMA methods of ACWR calculation and subsequent injury risk in elite Australian footballers.

5.3 Methods

5.3.1 Participants

Fifty-nine elite players from one club competing in the Australian Football League (AFL) (age, 23.5 ± 4.4 years; height, 189.7 ± 7.3 cm; mass, 88.9 ± 8.6 kg) participated in this two-year study. A total of 92 individual seasons were recorded, where 33 (56%) participants competed in both seasons and 26 (44%) participants competed in one season. Each season consisted of a 16-week pre-season phase comprising running and football-based sessions, followed by a subsequent 23-week in-season competitive phase. All experimental procedures were approved by The Australian Catholic University Human Research Ethics Committee.

5.3.2 Quantifying Workloads

Global positioning system (GPS) technology, sampling at 10 Hz (Optimeye S5; Catapult Innovations, Melbourne, Australia), was used to quantify training and match workloads of players. The GPS units also housed a tri-axial accelerometer, gyroscope, and magnetometer, each sampling at 100 Hz. This technology has demonstrated acceptable reliability and validity when measuring distance, velocity, acceleration, and player load [40, 67]. Workload variables consisted of; (1) total distance (m), (2) low-speed distance (<6.00 km.hr⁻¹), (3) moderate-speed distance (6.00–18.00 km.hr⁻¹), (4) high-speed distance (18.01–24.00 km.hr⁻¹), (5) very high-speed distance (>24.00 km.hr⁻¹), and (6) player load (au). Player load was measured as a modified vector magnitude using accelerometer data from each vector (X, Y, and Z axis), and was expressed as the instantaneous rate of change in each vector [67].
5.3.3 Definition of Injury

For the purpose of this study, and as previously used [25, 151], an injury was defined as any non-contact “time-loss” injury sustained during training or competition that resulted in a subsequent missed training session or missed game. Medical staff at the football club classified and maintained injury records throughout the study. Injury likelihoods were calculated based on the total number of injuries relative to the total exposure to a given workload range. Injury likelihoods and relative risks (RR) were calculated for both the present and subsequent week [136].

5.3.4 Acute:Chronic Workload Ratio Calculation

To calculate a daily rolling averages ACWR, one-week rolling workload data represented the acute workload, and the rolling four-week average workload data represented the chronic workload. If a player completed zero external workload (i.e. 0 meters run) in a week, these workload data were excluded in the week where no workload was performed, however these data were still included in the analysis of chronic workload. The ACWR was divided into the following ranges; (1) very low, ≤0.49, (2) low, 0.50–0.99, (3) moderate, 1.0–1.49, (4) high, 1.50–1.99, and (5) very high, ≥2.0 [9, 14, 151]. Each ACWR contained a unique amount of observations based on the data, ranging from 468 to 5722 observations.

5.3.4.1 Rolling Averages Acute:Chronic Workload Ratio

The rolling averages ACWR was calculated by dividing the acute workload by the chronic workload [9, 14, 151]. Where the chronic workload was greater than the acute workload, a
lower ACWR was recorded. Similarly, where the acute workload was greater than the chronic workload, a higher ACWR was recorded.

5.3.4.2 Exponentially Weighted Moving Averages Acute:Chronic Workload Ratio

The EWMA was calculated as described by Williams et al. [134]. The EWMA for a given day was calculated as:

$$EWMA_{today} = \text{Load}_{today} \times \lambda_a + ((1 - \lambda_a) \times EWMA_{yesterday})$$

Where $\lambda_a$ is a value between 0 and 1 that represents the degree of decay, with higher values discounting older observations in the model at a faster rate. $\lambda_a$ is calculated as;

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

Where $N$ is the chosen time decay constant, with one-week workload (i.e. 7 days) and four-week workload (i.e. 28 days) used to represent acute and chronic workloads, respectively. To calculate an EWMA ACWR value, an EWMA for acute workload (i.e. 7-day workload) and chronic workload (i.e. 28-day) was calculated using the above formula. The EWMA ACWR value was then calculated by dividing the EWMA acute workload by the EWMA chronic workload. To begin the EWMA calculation, the first observation in the series is arbitrarily recorded as the first workload value in the series. From this value, the aforementioned EWMA calculation can be used for acute and chronic workload calculation.
5.3.5 Statistical Analysis

Data were analysed using SPSS 24.0 (SPSS Inc., Chicago, IL, USA). The likelihood of sustaining an injury was analysed using two binary logistic regression models with significance set at \( p < 0.05 \). The ACWR was independently modelled as the predictor variable, and injury/no injury as the dependent variable. The very high ACWR (i.e. \( \geq 2.0 \)) was used as the reference group to which each other group was compared. Differences in ACWR calculation between the rolling averages ACWR model and the EWMA model for each ACWR ratio range were determined using a 1-way analysis of variance (ANOVA). The R-squared (\( R^2 \)) value for each model was determined, and logistic regression models were used to determine the differences between the models. Given the real-world nature of the study, magnitude-based inferences were used to determine any practically significant differences between groups, along with 95\% confidence intervals (CI) [137, 138]. Likelihoods were subsequently generated and thresholds for assigning qualitative terms to chances were assigned as follows: <1\%, almost certainly not; <5\%, very unlikely; <25\%, unlikely; <50\%, possibly not; \( \geq 50\% \), possibly; \( \geq 75\% \), likely; \( \geq 95\% \), very likely; \( \geq 99\% \), almost certainly. The magnitudes of differences between groups were considered practically meaningful when the likelihood was \( \geq 75\% \) [137, 138].

5.4 Results

5.4.1 Injuries

A total of 40 injuries were sustained during the two-year period. Of these, 18 were sustained during the pre-season period, and 22 were sustained during the in-season period. The
hamstring (53%) was the most commonly injured site, followed by other thigh injuries (i.e. quadriceps, adductors) (18%) and calf (18%).

5.4.2 Different Methods of ACWR Calculation

The average ACWR for each day over the duration of the study was calculated using the rolling averages and EWMA models and is displayed in Figure 5. The two methods of ACWR calculation were significantly different (p=0.001) and poorly related (R^2=0.43). Using the EWMA model for ACWR calculation resulted in a significantly lower value than that calculated by the rolling averages ACWR model for the same daily observations for moderate (mean±SD, 1.07±0.22 vs. 1.19±0.12; p=0.021), high (1.27±0.21 vs. 1.64±0.12; p=0.012) and very high (1.51±0.22 vs. 2.29±0.20; p=0.001) ACWR ranges. There were no significant differences (p>0.05) between the model calculations at a very low and low ACWR range.
Figure 5. The acute:chronic workload ratio (ACWR) modelled using each method: rolling averages and exponentially weighted moving averages.
5.4.3 Injury Likelihoods for each ACWR Model

5.4.3.1 Pre-Season

The likelihood of injury during the pre-season phase is shown in Figure 6. A rolling averages ACWR of >2.0 for total distance was significantly associated with an increased risk of injury compared to those with an ACWR of 1.0-1.49 (RR=8.41, 95% CI 1.09 to 64.93, p=0.048, 97.4% Very Likely). No other significant relationships were observed between the rolling averages ACWR and injury likelihood during the pre-season period. Using the EWMA model, there were multiple significant relationships shown between an ACWR of >2.0 and an increased injury likelihood when compared with lower ACWR ranges. Specifically, compared to an ACWR of 1.0-1.49, the likelihood of injury were increased 6- to 9-fold for: total distance (RR=8.74, 95% CI 7.35 to 10.39, p=0.002, 99.9% Almost Certainly), moderate-speed distance (RR=6.03, 95% CI 2.21 to 16.47, p=0.028, 98.4% Very Likely), and player load (RR=9.53, 95% CI 5.31 to 17.11, p=0.013, 99.3% Almost Certainly).
**Figure 6.** Likelihood of injury at each acute:chronic workload ratio range during the pre-season period for the current day for (a) total distance, (b) moderate-speed distance, (c) high-speed distance, and (d) player load. * denotes significantly different (p<0.05) from rolling averages ACWR model. RA=rolling averages. EWMA=exponentially weighted moving averages.
5.3.4.2 In-Season

During the in-season period, a rolling average ACWR of >2.0 had an increased likelihood of injury compared with a lower ACWR for a range of variables. When compared with an ACWR of 1.0-1.49, an ACWR of >2.0 was associated with an increase in injury risk for total distance (RR=6.52, 95% CI 4.83 to 8.80, p=0.008, 99.6% Almost Certainly), high-speed distance (RR=4.66, 95% CI 4.12 to 5.27 p=0.004, 99.8% Almost Certainly), and player load (RR=5.87, 95% CI 4.12 to 8.36, p=0.010, 99.4% Almost Certainly). Using the EWMA model, players who exceeded an ACWR of >2.0 experienced an injury risk 5–21 times greater than players who maintained an ACWR of 1.0-1.49 for total distance (RR=21.28, 95% CI 20.02 to 22.62, p=0.001, 99.9% Almost Certainly), moderate-speed distance (RR=18.19, 95% CI 17.17 to 19.27, p=0.001, 99.9% Almost Certainly), and player load (RR=13.43, 95% CI 12.75 to 14.14, p=0.001, 99.9% Almost Certainly) (Figure 7).
Figure 7. Likelihood of injury at each acute:chronic workload ratio range during the in-season period for the current day for (a) total distance, (b) moderate-speed distance, (c) high-speed distance, and (d) player load. * denotes significantly different (p<0.05) from rolling averages ACWR model. RA=rolling averages. EWMA=exponentially weighted moving averages.
5.4.4 Between-Model Comparisons

The variance ($R^2$) in injury for each variable for each model of ACWR calculation are shown in Table 5. While each model demonstrated significant relationships between very high ACWR results and injury likelihood during both the pre- and in-season periods, there were notable differences between the models. Using the rolling averages ACWR model, for total distance during the pre-season phase the regression equation demonstrates that $21\%$ ($R^2=0.21$) of the variance was explained using the ACWR. In comparison, $87\%$ of the variance ($R^2=0.87$, $p=0.042$) in injury likelihood was explained by the EWMA. During the pre-season period, the EWMA for high-speed distance and Player load explained $77\%$ ($R^2=0.77$, $p=0.041$) and $76\%$ ($R^2=0.76$, $p=0.044$), respectively, while the variance explained by the rolling averages ACWR was much lower ($R^2=0.13$ and $R^2=0.46$). Similarly during the in-season period, the $R^2$ value for each modelled variable was improved when using the EWMA model.
Table 5. Variance ($R^2$) in injury explained by the rolling daily averages and exponentially weighted moving averages ACWR models.

<table>
<thead>
<tr>
<th>Workload Variable</th>
<th>Rolling daily averages ACWR model</th>
<th>Exponentially weighted moving averages ACWR model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-Season</td>
<td>In-Season</td>
</tr>
<tr>
<td>Pre-Season</td>
<td></td>
<td></td>
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<tr>
<td>In-Season</td>
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</tbody>
</table>

Data are variance ($R^2$) with 95% confidence intervals. ACWR = acute:chronic workload ratio.

* denotes significantly different ($p < 0.05$) from rolling daily averages ACWR model.
5.5 Discussion

This study investigated if any differences existed between the previously described rolling averages model of ACWR calculation [9, 14, 151], and a new exponentially weighted moving averages ACWR calculation [134] in determining injury likelihood. Spikes in workload, resulting in an ACWR of >2.0, were significantly associated with an increase in injury risk irrespective of the model used. We also found significant differences in the values reported at moderate to very high ACWR ranges (i.e. 1.0-1.49, 1.50-1.99, and >2.0) between the two models, although no significant differences were reported at lower ACWR ranges (i.e. <0.49, 0.50-0.99). Further, our findings demonstrate that the EWMA model offers greater sensitivity in identifying injury likelihood at higher ACWR ranges (i.e. 1.50-1.99 and >2.0) during both the pre- and in-season periods.

5.5.1 Difference in ACWR Calculation between the Models

A key difference between the two proposed models of ACWR calculation is that the EWMA model assigns a decreasing weighting for each older workload value, whereas the rolling averages model suggests each workload in an acute and chronic period (typically 7 days and 28 days, respectively) is equal [134]. Similar to the rolling averages ACWR model, the EWMA model requires the calculation of both an EWMA acute and EWMA chronic workload value before the calculation of the EWMA ACWR. Unlike the rolling averages ACWR model, the values obtained for an EWMA acute and chronic workload, provided using the aforementioned formula, are not able to be considered in isolation due to weighting applied by the λa value. This is an important consideration given the protective effect of moderate-to-high chronic workloads against injury [9, 17, 151]. We modelled the daily average ACWR value for each day of the study period using both models and found that...
significantly lower ACWR values were obtained using the EWMA model at moderate, high, and very high ACWR ranges while no differences were observed at very low and low ACWR ranges. Given the current understanding of the relationship between very high ACWR ranges and subsequent increases in injury risk [9, 14, 133], the importance of this finding is two-fold. Firstly, rolling averages consider the relationship between load and injury as linear, and therefore all workload in a given timeframe is considered equal – when it is not. The EWMA model places a greater emphasis on the most recent workload a player has performed which will alter the ACWR value for a given day. Secondly, as the EWMA model alters the value for a given day, it influences where a player sits on the ACWR spectrum. If this increases their ACWR value it may place them in a ‘danger zone’ that would not be recognised using the rolling averages ACWR model. Therefore, if ACWR values differ at the higher end of the ACWR spectrum using each model, it is important to consider this and its subsequent effect on injury risk.

5.5.2 What Happens When Workloads are Spiked?

The findings of the present study demonstrate that large spikes in acute workload, relative to chronic workload, resulting in a very high ACWR were significantly associated with an increased risk of injury during both the pre- and in-season periods. This finding was replicated across both models, suggesting that regardless of which model of ACWR calculation was used – large spikes in workload, coupled with a very high ACWR, resulted in a significant increase in injury risk. The strength of the ACWR is that it considers the workload a player has performed, relative to the workload that the player has been prepared for [9, 23, 133], whilst also acknowledging that the way the load is achieved is as important as the ACWR itself [135, 152]. With that in mind it is clear that irrespective of the model
used, linear [9, 14, 135] or non-linear [134, 154], the use of the ACWR should be utilised to maximise performance in players through developing high chronic workloads to adequately prepare players for competition demands and minimising the risk of injury [9, 23].

5.5.3 The EWMA Model may be More Sensitive

A novel finding of this study is the relationship between a very high ACWR, calculated using the EWMA model, and an increase in injury risk during the pre-season period. Whilst the relationship between large spikes in workload and injury risk during the in-season period is well defined [151], the relationship during the pre-season period is not as clear. Unlike previous work in elite AF [151], our results demonstrate that using the EWMA model, large spikes in workload during the pre-season are associated with a significant rise in injury risk. It has previously been suggested that players are not as well equipped to handle spikes in workload during the in-season period as they are during the pre-season period due to increased match and physical demands [21, 139], coupled with an increased emphasis on performance and recovery. While the pre-season period is typically viewed as an opportunity to develop the required physical and physiological qualities to successfully compete during the in-season period [97], it is crucial that high workloads are prescribed systematically to apply adequate workloads to elicit a positive physiological change, whilst also minimising the negative physiological response [9, 97, 152]. It has been shown that greater amounts of training during the pre-season period may also offer a protective effect against injury during the subsequent in-season competitive period [15, 158], highlighting the further importance places on the pre-season period. Using the EWMA model it appears that large workload spikes, during either the pre- or in-season period are associated with a clear threshold (i.e. ACWR >1.50) where injury risk increases rapidly. The use of the EWMA model has
increased the sensitivity of injury likelihood suggesting that the rolling averages ACWR model does not; (1) accurately represent the variations in how workloads are accumulated (i.e. a workload performed 28 days ago is not equal to a workload performed 3 days ago) [134, 154], and (2) account for the decaying nature of fitness and fatigue effects over time [134, 154].

5.5.4 Potential Limitations

While the findings of the present study hold important implications for sports science and medicine staff, there are limitations that warrant further discussion. Firstly, the sample size was limited to 59 players from one club over a two-year period. It is difficult to draw competition-wide specific conclusions, as the findings may be reflective of this particular cohort of players at this particular point in time. Further, a small number of injuries (n=40) were recorded due to the inclusion criteria of only non-contact soft-tissue “time-loss” injuries as they are typically considered “workload-related” injuries. Further studies with players from multiple clubs, and a larger number of injuries would strengthen these findings. Secondly, no internal measures of workload (e.g. session rating of perceived exertion or heart rate) were included in the present study. The inclusion of these may be useful to further investigate the relationship between internal workload and injury likelihood. While the majority of statistical information provided in this study stems from logistic regression models, we acknowledge that by running multiple models, and thus multiple comparisons, the risk of a type I error may be inflated. Finally, our results may be influenced by a smaller sample size at the extremities of ACWR ranges (i.e. >2.0). This may be due to established load monitoring systems to reduce the number of exposures to very high ACWR ranges.
5.6 Conclusions

In this first study to investigate the difference between two proposed models of ACWR calculation and injury likelihood in elite Australian football players, a high ACWR was significantly associated with an increase in injury risk for both models. Further, the EWMA model had significantly greater sensitivity to detect increases in injury likelihood at higher ACWR ranges during both the pre- and in-season periods. This finding supports the refinement of the current ACWR model, although the concept that a player performing greater workload than what they are prepared for is reinforced. While the ACWR model may be refined to increase sensitivity, the basic concept of building chronic workloads to prepare players to tolerate acute workloads will remain the same. Similarly, the ACWR should not be considered in isolation, but rather in context with acute and chronic workload. Future work should attempt to quantify the direct (i.e. medical expenses, financial loss) and indirect (i.e. missed training and competition, etc.) costs of workload-related (i.e. spikes in workload) injuries and/or the longitudinal effects of controlled training loads on injury rates as this may provide greater insight than continued risk factor analysis.

5.7 What are the New Findings?

- The EWMA model is more sensitive to detect increases in injury risk at higher ACWR ranges during both the pre- and in-season periods.
- The EWMA model may be better suited to modelling workloads and injury risk than the rolling averages ACWR model.
- Irrespective of ACWR model used, large spikes in acute workload are significantly associated with an increase in injury risk.
5.8 How Might this Impact on Clinical Practice in the Near Future?

- Sharp spikes in workload for multiple variables should be avoided, as they are associated with an increase in injury risk.
- The rolling averages model is evidence-based and supported by available literature to quantify injury risk, however the exponentially weighted moving averages model to calculate ACWR has greater sensitivity for detecting increases in injury risk at higher ACWR ranges and therefore should be used to model workloads and injury risk.
- Providing more evidence around different methods of ACWR calculation and injury risk will enable practitioners involved in the physical preparation of elite players to systematically and ‘safely’ prescribe high training loads to enhance the physical qualities required to not only compete, but succeed, at the highest level of their chosen sport whilst minimising the risk of workload-related injury.

5.9 Acknowledgements

The authors would like to thank the players of the Brisbane Lions Australian Football Club for their participation in this study.
Chapter 6

Study 4 – The use of individualised speed zones in Australian Football: Are we really measuring what we think we are?

This study has been accepted for publication following peer review. Full reference details are:

6.1 Abstract

Objectives: This study aimed to examine the difference between absolute and relative workloads, injury likelihood, and the acute:chronic workload ratio (ACWR) in elite Australian football.

Design: Single cohort, observational study.

Methods: Forty-five elite Australian football players from one club participated in this study. Running workloads of players were tracked using Global Positioning System technology, and were categorised using either; (1) absolute, pre-defined speed thresholds, or (2) relative, individualised speed thresholds. Players were divided into three equal groups based on maximum velocity; (1) faster, (2) moderate, or (3) slower. One-week and four-week workloads were calculated, along with the ACWR. Injuries were recorded if they were non-contact in nature and resulted in “time-loss”.

Results: Faster players demonstrated a significant overestimation of very high-speed running when compared to their relative thresholds (p=0.01, ES=-0.73). Similarly, slower players demonstrated an underestimation of high- (p=0.06, ES=0.55) and very high-speed (p=0.01, ES=1.16) running when compared to their relative thresholds. For slower players, (1) greater amounts of relative very high-speed running had a greater risk of injury than less (RR=8.30, p=0.04), and (2) greater absolute high-speed chronic workloads demonstrated an increase in injury likelihood (RR=2.28, p=0.16), while greater relative high-speed chronic workloads offered a decrease in injury likelihood (RR=0.33, p=0.11). Faster players with a very high-speed ACWR of >2.0 had a greater risk of injury than those between 0.49-0.99 for both absolute (RR=10.31, p=0.09) and relative (RR=4.28, p=0.13) workloads.
**Conclusions:** The individualisation of velocity thresholds significantly alters the amount of very high-speed running performed and should be considered in the prescription of training load.
6.2 Introduction

Australian Football (AF) is a fast-paced, highly intermittent sport requiring players to perform high-intensity activities (i.e. sprinting, running, and physical contacts) interspersed with low-speed (i.e. walking and jogging) movements [28, 31]. It is common practice in elite sporting organisations to use Global Positioning System (GPS) technology to provide information on the activity profiles of players during training and competition [25, 29, 30]. With the physical demands of AF increasing [64], it is critical that strength and conditioning staff prescribe an appropriate training stimulus to enhance the individual physical qualities of players in their squads.

While activity profiles have been extensively researched [1, 30, 31], a common methodological limitation is the sole use of absolute, pre-defined speed thresholds rather than thresholds that are calculated relative to an individual’s capacity [76]. It has been proposed that faster players may perform at a relatively lower percentage of their maximum capacity when compared with slower players who may perform at a relatively higher percentage of their maximum capacity [71]. If a discrepancy exists between absolute and relative quantification of workload, this has significant implications when planning individualised training programs, accurately quantifying an individual’s training loads, and the relative stress and recovery status of the player [76]. In junior rugby league players, it was reported that match intensity increased as age increased if data were reported according to pre-defined absolute thresholds, however when expressed relative to individual sprinting capacity, younger players exhibited higher playing intensities and performed greater amounts of high-speed running (HSR) [71]. Similarly in comparison to a standardised HSD threshold of 5 m.s⁻¹, using a relative HSR threshold of 60% of maximum velocity resulted in a significant underestimation of HSR in professional rugby union forwards, and a significant
overestimation of HSR in the backs positional group [76]. Further, in work conducted during professional soccer match-play [72], there were significant differences in high-intensity distance run when a relative HSR threshold was used – rather than an absolute speed threshold [72]. Abt and Lovell [72] found that high-speed running was substantially underestimated when using a pre-defined absolute high-speed running threshold of 19.8 km.hr$^{-1}$. Collectively, these findings suggest that the sole use of an arbitrary, absolute, pre-defined speed threshold may under- or over-estimate the true physical demands of training and competition.

In AF the session rating of perceived exertion (RPE) [25] and GPS-derived running loads [24] have been used to compare injury risk with absolute workloads (i.e. 1-week, or 3-week), or previous-to-current week changes in load. In recent injury investigations in cricket [14], rugby league [16, 17], Gaelic football [108], Australian football [151, 159], and elite youth football [111], the acute:chronic workload ratio (ACWR) has been used to compare the acute workload (i.e. workload performed in one week), with the chronic workload (i.e. rolling 4-week average workload) as a ratio to give a representation of a player’s “preparedness” to train or play [9]. There are two general findings across these sports; 1) higher chronic workloads may offer a protective mechanism against injury, and 2) large spikes in workload, reflected by a very high acute:chronic workload ratio (i.e. >2.0), are associated with an increased risk of injury in both the current [16, 17, 151] and subsequent week [14, 17, 151]. Specifically in AF, using absolute velocity thresholds, sharp increases in high-speed running load (i.e. ACWR >2.0) have been associates with an increased risk of injury using both a rolling averages model (RR=11.62, $P=0.006$) [151], and more recently an exponentially weighted moving averages (EWMA) model (RR=4.66, $P=0.004$) [159]. Although these
findings are significant, we are currently unaware of the relationship between relative running loads and injury risk in elite AF players.

To date, no research has investigated the differences in absolute and relative external workloads through the use of relative speed thresholds in elite AF. Therefore, the aim of the present study was to investigate the differences in activity profiles when data are expressed as both an absolute threshold, and relative to the individual player’s maximum velocity. A second aim was to examine if the use of relative acute and chronic running workloads, and the acute:chronic workload ratio were associated with subsequent injury risk in elite Australian footballers.

6.3 Methods

6.3.1 Participants

Forty-five elite AF players from one club (mean ± SD age, 22 ± 3 years; height, 190 ± 7 cm; mass, 89 ± 8 kg) participated in this study. Data were collected over the course of one Australian Football League (AFL) season consisting of a 16-week pre-season period, which included running and football-based sessions, and a subsequent 23-week in-season competitive period. All participants received a clear explanation of the study, including detailed information on the risks and benefits of participation and provided written informed consent. The Australian Catholic University Human Research Ethics Committee approved all experimental procedures (Approval Number 2016-40E).
6.3.2 Monitoring Workloads

Data were collected using GPS technology sampling at 10 Hz (Optimeye S5, Catapult Innovations, Melbourne, Victoria, Australia), which provided information on the movement demands of players across the season. The GPS unit also housed a tri-axial accelerometer, gyroscope, and magnetometer sampling at 100 Hz. This technology has demonstrated acceptable validity and reliability when measuring velocity, distance, and accelerations in both laboratory- and field-based testing [40, 67]. Further, when compared with earlier models (i.e. 1 Hz and 5 Hz), 10 Hz GPS units are the most valid and reliable within both linear, change of direction, and team sport simulated testing conditions to provide information on the physical movement demands of training and match-play [38, 160].

Maximum velocity was tracked across the season using GPS technology, as no significant differences have been found for speed measures assessed using timing gates and GPS devices in a cohort of team sport players [161]. Each player wore the same unit for each session, and data were analysed using the same software for the duration of the study (Catapult Openfield v1.13.1, Catapult Innovations, Melbourne, Victoria, Australia) [161]. Absolute workload data were expressed as the total running distance players completed at low (<6 km.hr\(^{-1}\)), moderate (6–18 km.hr\(^{-1}\)), high (18–24 km.hr\(^{-1}\)), and very high (>24 km.hr\(^{-1}\)) speeds as both absolute pre-defined speed zones, and relative to the individual player’s maximum velocity. The maximum velocity of each participant was determined at the beginning of the season. If a player achieved a higher maximum velocity in training (which included dedicated speed training sessions) or competition, this then became their new maximum velocity for the remainder of the data collection period.
6.3.3 Calculating Relative Workloads

In order to calculate a player’s individual thresholds, the average maximum velocity (32.1 km.hr\(^{-1}\)) was used as a reference to create the relative thresholds for each speed zone. Each relative zone was calculated as a percentage of the absolute thresholds defined above and then rounded to enhance the practical application of the data. The relative thresholds that were applied, based on an individual’s maximum velocity, were; low (0-19.99%), moderate (20-54.99%), high (55-74.99%), and very high (>75%). These relative zones closely reflected the absolute zones of; low (<6 km.hr\(^{-1}\)), moderate (6–18 km.hr\(^{-1}\)), high (18–24 km.hr\(^{-1}\)), and very high (>24 km.hr\(^{-1}\)), and were chosen to closely replicate relative high-speed running thresholds used previously [71, 76]. To assess the differences between absolute and relative workloads, players were divided equally into thirds to either a (i) faster (maximum velocity >32.70 km.hr\(^{-1}\), n = 15), (ii) moderate (maximum velocity 31.70–32.69 km.hr\(^{-1}\), n = 15) or (iii) slower (maximum velocity <31.69 km.hr\(^{-1}\), n = 15) group based on the maximum velocity reached across the season.

Acute and chronic workload were calculated as rolling averages using 7- and 28-days respectively as described by Hulin et al. [14] and the EWMA acute:chronic workload ratio data were calculated using the methods described by Murray et al. [159]. Workload variables were divided into logical increments to enhance the application of the findings to the real-world. The chosen increments were the same across both acute and chronic workload variables. The EWMA acute:chronic workload ratio was divided into the following ranges; (a) very low, \(≤0.49\), (b) low, 0.50-0.99, (c) moderate, 1.0-1.49, (d) high, 1.50-1.99, and (e) very high, \(≥2.0\). An injury was defined as any non-contact “time-loss” injury obtained during training or competition that resulted in a missed training session or game [25, 151]. Medical
staff at the football club classified all injuries and updated relevant injury databases throughout the season. Injury likelihoods were calculated based on the total number of injuries sustained, relative to the total number of players exposed to each given workload category. Injury likelihoods and risks (RR) for both the current week, and subsequent week were calculated [136].

6.3.4 Statistical Analysis

Data were analysed using SPSS 24.0 (SPSS Inc., Chicago, IL, USA). Distance covered in each of the absolute and relative zones were compared using multiple one-way analyses of variance (ANOVA) to determine if there were significant differences between conditions (i.e. absolute and relative). The GPS data was log-transformed to provide the coefficient of variation (CV), which is the variation of performance expressed as a percentage of the average performance. Further, the between-subject standard deviation was calculated and expressed as a percentage. The between-subject standard deviation was multiplied by 0.2 to determine the smallest worthwhile change (SWC) for each variable. The minimum criterion change required to produce a probable significant change in performance was calculated as previously described [137, 148]. The likelihood of sustaining an injury was analysed using two binary logistic regression models with significance set at $P < 0.05$. Acute and chronic workloads, and the acute:chronic workload ratio were independently modelled as predictor variables (for both absolute and relative thresholds), and injury/no injury as the dependent variable. The very high acute:chronic workload ratio (i.e. >2.0) group was used as the reference group to which each other group was compared. Given the real-world practical nature of the study, magnitude-based inferences were used to determine the Cohen’s Effect Size (ES) statistic and 90% confidence intervals (CI) [148]. Effect sizes of <0.2, 0.21–0.60,
0.61–1.20, and >1.20 were considered trivial, small, moderate, and large, respectively [148]. Likelihoods were subsequently generated and thresholds for assigning qualitative terms to chances assigned. The magnitude of differences between groups were considered practically meaningful when the likelihood was $\geq 75\%$ [137, 138].

6.4 Results

Absolute and relative weekly average workload for the duration of the study is presented in Table 6. Moderate-speed distance was significantly lower when quantified using relative workload than absolute workload ($p=0.03$, ES=$-0.45$ (90% CI $-0.80$–$-0.11$), 89% Likely). No other significant differences were found between absolute and relative weekly average workload for the group. The variability of the measured variables across the season are presented in Table 6. The actual percentage difference in absolute and relative workloads for high-speed distance (in slower players) and very high-speed distance (in slower and faster players) was greater than the minimum criterion change required to produce a practically meaningful difference in performance.
Table 6. Weekly descriptive statistics for all participants’ external workload variables, both absolute and relative, over the duration of the study.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Absolute Workload</th>
<th>Relative Workload</th>
<th>P-value</th>
<th>Effect Size (90% CI)</th>
<th>Likelihood</th>
<th>%CV</th>
<th>SWC%</th>
<th>Prob. Change%</th>
<th>Actual Diff%</th>
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</thead>
<tbody>
<tr>
<td><strong>All Players</strong></td>
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<tr>
<td>LSD (m)</td>
<td>5766.6 ± 3209.3</td>
<td>6041.2 ± 3358.3</td>
<td>0.29</td>
<td>0.23 ( -0.13 – 0.58)</td>
<td>55% Possibly</td>
<td>4.5</td>
<td>3.5</td>
<td>8.0</td>
<td>6.0</td>
</tr>
<tr>
<td>MSD (m)</td>
<td>12375.4 ± 6266.8</td>
<td>11611.8 ± 5842.5</td>
<td>*† 0.03</td>
<td>-0.45 ( -0.80 – 0.11)</td>
<td>89% Likely</td>
<td>3.9</td>
<td>2.4</td>
<td>6.3</td>
<td>6.9</td>
</tr>
<tr>
<td>HSD (m)</td>
<td>2704.9 ± 1726.4</td>
<td>2929.3 ± 1889.0</td>
<td>0.21</td>
<td>0.27 ( -0.08 – 0.62)</td>
<td>63% Possibly</td>
<td>11.3</td>
<td>5.7</td>
<td>17.0</td>
<td>11.8</td>
</tr>
<tr>
<td>VHSD (m)</td>
<td>371.1 ± 284.1</td>
<td>443.7 ± 436.3</td>
<td>0.16</td>
<td>0.30 ( -0.05 – 0.65)</td>
<td>68% Possibly</td>
<td>40.1</td>
<td>8.4</td>
<td>48.5</td>
<td>35.6</td>
</tr>
<tr>
<td><strong>Faster Players</strong></td>
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<tr>
<td>LSD (m)</td>
<td>5472.8 ± 681.7</td>
<td>5865.2 ± 679.2</td>
<td>† 0.13</td>
<td>0.56 ( -0.04 – 1.17)</td>
<td>84% Likely</td>
<td>2.9</td>
<td>2</td>
<td>6.7</td>
<td>16.6</td>
</tr>
<tr>
<td>MSD (m)</td>
<td>12353.8 ± 1297.4</td>
<td>11992.9 ± 1423.6</td>
<td>0.47</td>
<td>-0.27 ( -0.89 – 0.36)</td>
<td>57% Possibly</td>
<td>2.0</td>
<td>2.4</td>
<td>4.4</td>
<td>3.1</td>
</tr>
<tr>
<td>HSD (m)</td>
<td>3132.1 ± 673.6</td>
<td>2955.8 ± 757.2</td>
<td>0.51</td>
<td>-0.25 ( -0.88 – 0.38)</td>
<td>55% Possibly</td>
<td>6.7</td>
<td>5.2</td>
<td>11.9</td>
<td>6.6</td>
</tr>
<tr>
<td>VHSD (m)</td>
<td>495.2 ± 201.8</td>
<td>342.0 ± 146.4</td>
<td>*† 0.02</td>
<td>-0.81 ( -1.38 – 0.23)</td>
<td>96% Very Likely</td>
<td>16.6</td>
<td>8.6</td>
<td>25.2</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Moderate Players</strong></td>
<td></td>
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<td></td>
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<tr>
<td>LSD (m)</td>
<td>5458.4 ± 947.0</td>
<td>5826.4 ± 1031.9</td>
<td>0.32</td>
<td>0.37 ( -0.25 – 0.99)</td>
<td>68% Possibly</td>
<td>3.0</td>
<td>3.8</td>
<td>6.8</td>
<td>6.5</td>
</tr>
<tr>
<td>MSD (m)</td>
<td>12103.6 ± 1546.6</td>
<td>11323.0 ± 1582.7</td>
<td>† 0.18</td>
<td>-0.49 ( -1.10 – 0.12)</td>
<td>79% Likely</td>
<td>4.3</td>
<td>2.9</td>
<td>7.2</td>
<td>6.8</td>
</tr>
<tr>
<td>HSD (m)</td>
<td>2703.7 ± 749.6</td>
<td>2884.0 ± 803.1</td>
<td>0.53</td>
<td>0.23 ( -0.39 – 0.86)</td>
<td>54% Possibly</td>
<td>4.3</td>
<td>6.1</td>
<td>10.4</td>
<td>6.6</td>
</tr>
<tr>
<td>VHSD (m)</td>
<td>362.8 ± 92.8</td>
<td>398.7 ± 136.9</td>
<td>0.41</td>
<td>0.31 ( -0.32 – 0.94)</td>
<td>61% Possibly</td>
<td>15.9</td>
<td>5.9</td>
<td>21.8</td>
<td>19.5</td>
</tr>
<tr>
<td><strong>Slower Players</strong></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>LSD (m)</td>
<td>5462.7 ± 1391.3</td>
<td>5425.7 ± 1501.7</td>
<td>0.94</td>
<td>-0.03 ( -0.66 – 0.61)</td>
<td>40% Possibly</td>
<td>4.5</td>
<td>6.7</td>
<td>16.6</td>
<td>6.7</td>
</tr>
<tr>
<td>MSD (m)</td>
<td>12724.1 ± 2216.3</td>
<td>11464.6 ± 2199.7</td>
<td>† 0.13</td>
<td>-0.56 ( -1.16 – 0.05)</td>
<td>84% Likely</td>
<td>3.5</td>
<td>4.5</td>
<td>8.0</td>
<td>10.8</td>
</tr>
<tr>
<td>HSD (m)</td>
<td>2772.8 ± 890.1</td>
<td>3457.8 ± 1105.4</td>
<td>† 0.07</td>
<td>0.66 ( 0.06 – 1.25)</td>
<td>90% Likely</td>
<td>8.8</td>
<td>7.7</td>
<td>16.5</td>
<td>21.7</td>
</tr>
<tr>
<td>VHSD (m)</td>
<td>267.5 ± 85.6</td>
<td>503.0 ± 1416.3</td>
<td>*† 0.01</td>
<td>1.40 ( 0.95 to 1.85)</td>
<td>99% Almost Certain</td>
<td>24.8</td>
<td>6.9</td>
<td>31.7</td>
<td>20.7</td>
</tr>
</tbody>
</table>

Note: *Denotes significantly different from absolute workload. †Denotes practically meaningful difference from absolute workload.
Multiple significant relationships were found for high, and very-high speed distance when data were expressed as either absolute or relative speeds. Specifically, faster players experienced a significant overestimation of very high-speed running when absolute workload thresholds were used compared with the use of relative workload thresholds (p=0.02, ES=-0.81 (90% CI -1.38—0.23), 96% Very Likely). In addition, faster players performed relatively greater low-speed running when compared with the absolute workload threshold (p=0.13, ES=0.56 (90% CI -0.04–1.17), 84% Likely). In contrast, slower players performed relatively less moderate-speed running when the relative workload thresholds were applied (p=0.13, ES=-0.56 (90% CI -1.16–0.05), 84% Likely). There was a moderate underestimation of high-speed (p=0.07, ES=0.66 (90% CI 0.06–1.25), 90% Likely) and very high-speed running (p=0.01, ES=1.40 (90% CI 0.95–1.85), 99% Almost Certainly) when using relative workload (Figure 8) (Table 6).
Figure 8. Absolute and relative average weekly workloads of faster (a, b, c, d) and slower (i, j, k, l) players across the duration of the pre- and in-season periods. * Denotes significant (p<0.05) difference from absolute workload. † Denotes a practically meaningful (likelihood ≥75%) difference from absolute workload.
Over the duration of the study, 31 injuries were recorded. The most common site of injury was the hamstring (29%), followed by the groin/hip flexor (25%), and calf (13%). Using absolute workloads, faster players with an acute high-speed distance workload of >3000 m had a greater risk of injury compared to those with a high-speed distance workload of <2000 m (RR=4.26, 90% CI 1.64 to 11.04, p=0.06, 96.2% Very Likely) and 2500 – 3000 m (RR=3.96, 90% CI 0.26 to 60.60, p=0.19, 88.9% Likely). Similarly when relative workloads were applied, faster players with an acute high-speed distance workload of >3000 m had a significantly greater risk of injury than those who completed <2000 m (RR=4.82, 90% CI 2.24 to 10.37, p=0.04, 97.2% Very Likely). In addition, slower players who completed >3000 m of absolute high-speed distance in an acute period had an increased risk of injury compared with those who completed both <2000 m of absolute (RR=4.18, 90% CI 1.21 to 14.46, p=0.08, 95.1% Very Likely), and relative (RR=4.23, 90% CI 0.30 to 60.54, p=0.18, 89.7% Likely) distance, and 2001-2500 m of absolute (RR=3.07, 90% CI 0.08 to 48.11, p=0.30, 82.3% Likely) distance, respectively. Further, with the application of relative thresholds, slower players with an acute relative very high-speed distance >1500 m experienced a greater injury risk than those who completed <500 m (RR=8.30, 90% CI 3.02 to 22.77, p=0.04, 97.4% Very Likely), and 501-1000 m (RR=4.53, 90% CI 0.24 to 85.16, p=0.19, 89.3% Likely), but not 1001-1500 m (Figure 9).
Figure 9. Likelihood of injury at differing acute workload ranges for faster (low-speed, A; moderate-speed, B; high-speed, C; very high-speed, D) and slower (low-speed, E; moderate-speed, F; high-speed, G; very high-speed, H) players. * Denotes a significant (p<0.05) difference from the reference group. † Denotes a practically meaningful (likelihood ≥75%) difference from the reference group.
In regard to chronic workload for slower players, a higher absolute chronic workload (>3000 m) for high-speed distance was associated with an increased risk of injury when compared with a lower chronic workload of < 2000 m (RR=2.28, 90% CI 0.14 to 36.57, p=0.16, 80.9% Likely). However, a higher relative chronic workload (>3000 m) for high-speed distance was associated with a decreased injury risk for slower players when compared with a lower chronic workload of 2000-2500 m (RR=0.33, 90% CI 0.09 to 1.22, p=0.11, 93% Likely). There were no other significant differences in chronic workload for faster or slower players when absolute and relative thresholds were applied (Figure 10).
Figure 10. Likelihood of injury at differing chronic workload ranges for faster (low-speed, A; moderate-speed, B; high-speed, C; very high-speed, D) and slower (low-speed, E; moderate-speed, F; high-speed, G; very high-speed, H) players. * Denotes a significant (p<0.05) difference from the reference group. † Denotes a practically meaningful (likelihood ≥75%) difference from the reference group.
An ACWR of >2.0 for faster players using absolute workloads was associated with a significantly greater risk of injury than those with an ACWR of 0.49-0.99 for low- (RR=32.40, 90% CI 27.27 to 38.50, p=0.01, 99.7% Almost Certainly), moderate- (RR=21.12, 90% CI 8.26 to 53.99, p=0.03, 98.4% Very Likely), high- (RR=5.85, 90% CI 1.93 to 17.70, p=0.05, 96.5% Very Likely), and very high-speed (RR=10.31, 90% CI 0.98 to 58.85, p=0.10, 94.5% Likely) distance. Further, a greater ACWR (>2.0) for very high-speed distance was also associated with an increase in injury risk when compared with an ACWR of <0.49 (RR=4.77, 90% CI 0.07 to 69.85, p=0.25, 85.7% Likely). These findings were replicated when relative workloads were applied to faster players, where an ACWR of >2.0, when compared with 0.49 to 0.99, for low- (RR=32.65, 90% CI 28.43 to 37.49, p=0.01, 99.8% Almost Certainly), moderate- (RR=21.00, 90% CI 7.98 to 55.23, p=0.03, 98.3% Very Likely), high- (RR=5.52, 90% CI 2.49 to 12.16, p=0.04, 97.4% Very Likely), and very high-speed (RR=4.28, 90% CI 0.13 to 139.73, p=0.13, 87.0% Likely) distance resulted in a significant increase in injury risk. No significant findings were found for slower players using either absolute or relative workloads due to no injuries occurring in the reference group range of >2.0 (Figure 11).
**Figure 11.** Likelihood of injury at differing acute:chronic workload ratio ranges for faster (low-speed, A; moderate-speed, B; high-speed, C; very high-speed, D) and slower (low-speed, E; moderate-speed, F; high-speed, G; very high-speed, H) players. * Denotes a significant (p<0.05) difference from the reference group. † Denotes a practically meaningful (likelihood ≥75%) difference from the reference group.
6.5 Discussion

The present study investigated the weekly running demands of elite Australian football players using both absolute (i.e. pre-defined) and relative (i.e. relative to a players’ individual maximum velocity) speed thresholds. Consistent with previous findings [71, 76], when using relative speed thresholds slower players completed significantly greater amounts of high- and very high-speed running, whereas faster players completed significantly less very high-speed running compared with the use of absolute thresholds. Further, slower players who performed greater amounts of acute relative very high-speed running demonstrated a greater risk of injury than those who completed less relative very high-speed running. Additionally, a higher absolute chronic workload for high-speed distance for slower players resulted in a practical increase in injury likelihood, while a higher relative chronic high-speed distance for slower players offered a practically decreased likelihood of injury. Finally, we also found that spikes in workload, resulting in an ACWR of >2.0, were associated with a significant rise in injury likelihood for faster players, but not slower players.

The present study is the first to examine the application of absolute and relative thresholds in elite Australian football; although not the first in team sport [71, 72, 76]. Our findings demonstrate that significant differences in very high-speed running exist when data are expressed relative to an individual’s capacity. Specifically, when applying a relative threshold to slower players, their amount of very-high speed running is significantly increased. The opposite effect occurs in faster players, where a relative threshold significantly decreases their amount of very high-speed running. The use of absolute speed thresholds is important to allow the comparison of players’ performance across positional groups during training and match-play [76]. However, this method fails to account for individual variation, particularly in maximum velocity, across a playing group when considering the same
absolute workload. Gabbett [71] suggested that two players who completed the same absolute amount of very high-speed running would result in a significantly greater strain on the player with a slower maximum velocity. This finding highlights the need to consider both absolute and relative demands of training and competition to prescribe an adequate training stimulus at an individual player level [71, 76].

A key finding was the difference in injury likelihood in acute very high-speed distance for slower players when data were expressed using a relative threshold. While no difference was found when using absolute workloads, the relative risk of injury was 8.3 and 4.5 times greater when a slower player completed >1500 m of relative very high-speed running compared with <500 m and 501-1000 m, respectively. The implications of this finding are two-fold; 1) slower players fail to reach high amounts of absolute very high-speed distance, with no injuries occurring at the highest ranges with only minimal exposure, and 2) when an individual threshold is applied and slower players complete large amounts of very high-speed running in an acute 7-day window, their risk of injury significantly increases.

Further, a higher absolute chronic high-speed workload for slower players practically increased their risk of injury, however a higher relative chronic high-speed workload for slower players offered a practically decreased risk of injury. The notion that moderate-to-high chronic workloads may offer a protective effect against injury is not new, with a series of papers in multiple sports reporting similar findings [17, 27], as well as specifically in AF [98, 151]. This finding suggests that slower players who complete greater amounts of absolute high-speed running may be performing above their high-speed running “threshold” which contributes to a higher injury risk, however when compared to their relative threshold it
offers a protective effect. This highlights the need for individualisation of high-speed running thresholds to gain a true understanding of injury risk at an individual player level. Further, it demonstrates that, for slower players, gradual building of relative high-speed running loads may offer a protective effect against injury, as opposed to building absolute high-speed running loads which may increase the likelihood of injury for this cohort of players. While this finding demonstrates the importance of understanding the relative stress placed on an individual, it is also important to note that demands of competition are absolute. That is, it is irrelevant how ‘relatively’ fast a player is moving in a game, the player with a greater absolute maximum velocity will move faster. To mitigate this we can (1) select players with greater maximum velocity, and (2) increase speed through an adequate and specific training program, typically during the pre-season period.

The use of the EWMA model for ACWR calculation has only recently been proposed in the scientific literature [159], although a rolling average ACWR model has been examined multiple times before [9, 17, 111]. The findings of this study extend recent work in Australian football [98, 151, 159], rugby league [16, 17], cricket [14], soccer [111, 127], and Gaelic football [27, 108], which have collectively reported that large spikes in workload, resulting in a very high ACWR, were associated with a significant increase in injury risk. When categorised by maximum velocity, faster players exhibited a similar trend where a significant increase in injury likelihood at a very high ACWR range for each variable, both absolute and relative, was demonstrated. This supports the previously raised notion [9] that there is a clear workload threshold where injury risk rises rapidly. Interestingly, no significant relationships between the EWMA ACWR and injury risk in the cohort of slower players in the present study. A possible explanation for this finding is the number of injuries recorded in the reference group of ACWR >2.0 (n=0). While significant differences were exhibited in the
amount of very high-speed running recorded when data were expressed using absolute or relative thresholds, these differences did not translate to differences in injury likelihood in slower players. A further explanation for this finding may be that slower players were more tolerant to changes in ACWR because the absolute force (i.e. absolute very high-speed running) placed on their body was less than faster players. We suggest that further work, with a larger sample size of injuries should be considered before drawing definitive conclusions regarding differences in injury risk for faster or slower players.

While this study is one of the first to investigate the use of relative speed thresholds in elite sport, there are some limitations that should be considered. First, the findings of the present study may be limited to this particular group of players from one club competing in the Australian Football League (AFL). Second, there are currently no universally accepted and standardised speed zones for the use of GPS technology across a range of team sports. The absolute speed thresholds in the present study are consistent with some [151, 159], but not all [24, 71, 72], reported studies in the literature. While the GPS units used in this study provide a valid measure of maximum velocity when compared with a radar gun, it should be noted that there is a small error associated with the measurement of this quality when using GPS (Typical Error of the Estimate = 1.87 [90% CI 1.65 to 2.18%]) [161]. The cohort of elite Australian footballers in this investigation did not undertake routine maximum velocity testing; the use of GPS technology represented the most practical alternative to timing gates for testing this quality. However, it should be noted that all recommendations for the use of GPS monitoring of field-based athletes [38, 160, 161], were followed when assessing maximum velocity over time. Finally, in the present study, the actual difference in absolute and relative workloads for high- and very high-speed distance was greater than the minimum criterion change required to produce a probable significant difference in performance.
However, given the large variability in AF activity profiles as the speed of movement increases, sport scientists should be cautious when interpreting very high-speed running data. Further studies comparing data across a number of teams and a broader group of Participants may decrease the “noise” in the measurement of these variables, while also providing further insight on the absolute and relative running demands of AF.

**6.6 Practical Applications**

The findings of the present study demonstrate differences in player workload, specifically in very high-speed running, when data are expressed using either absolute or relative thresholds. These findings are important for those involved in the physical preparation, development, and monitoring of Australian football players. Specifically, conditioning staff should consider both the absolute and relative demands of training and competition to provide a comprehensive assessment of workload performed by a given player. By doing so, conditioning staff can prescribe an appropriate individualised training stimulus, in order to elicit a positive physiological response whilst minimising the risk of injury and negative responses associated with training. Further, large spikes in workload resulting in a very high ACWR (i.e. >2.0) for both absolute and relative thresholds, were significantly associated with an increased risk of injury in this cohort of Australian football players.
6.7 Conclusions

This is the first study to examine the differences between absolute and relative thresholds in elite Australian football players. Our findings demonstrate that, 1) differences in very high-speed running exist when data are expressed as either absolute or relative speed thresholds for faster and slower players, 2) large spikes in workload, irrespective of method used resulted in an increased risk of injury at higher ACWR ranges, and 3) higher relative chronic workloads for high-speed distance for slower players may offer a protective effect against injury, while higher absolute chronic workloads for high-speed distance may increase the likelihood of injury. These findings support earlier work, and suggest that practitioners should consider the running demands of each player on an individual basis.

6.8 Acknowledgements

The authors wish to extend their thanks to players and staff of the Brisbane Lions Football Club for their ongoing support of our research and their contribution to this study. NM was supported through an Australian Government Research Training Program Scholarship.
Chapter 7

Study 5 – Exponentially weighted moving averages vs. rolling averages: a case series of differing loading patterns

This study has been prepared and submitted for publication as a book chapter in Common Foot and Ankle Injuries: The Complete Guide for Physical Therapists (Lotus Publishing).
7.1 Abstract

**Objectives:** To describe the differences in loading patterns between the rolling averages (RA) and exponentially weighted moving averages (EWMA) models of acute:chronic workload ratio (ACWR) calculation. A secondary aim was to assess how ‘spikes’ in workload (and ACWR) can occur in one, or both of the models.

**Design:** Single cohort, case series.

**Methods:** The loading patterns of three Australian football players; 1) returning from injury, 2) playing regularly, but not training consistently, and 3) with a consistent playing and training schedule, were monitored. A 28-day period was arbitrarily chosen for each player, with daily workloads, along with acute and chronic workload values, and ACWR calculated for each model.

**Results:** The values calculated for the acute \( r = 0.23 \) and chronic \( r = 0.26 \) workload variables were poorly correlated between the calculated models. Further, the relationship between the two calculated ACWR models was moderate \( r = 0.40 \) suggesting there is a meaningful difference in the values calculated.

**Conclusions:** Differences exist in the values produced by these models, as demonstrated by the weak relationships found. These differences likely exist due to the differences in the weighting of the models, where one model treats all workload within a given period as equal (RA), and one model places a greater emphasis on the more recent workload performed (EWMA). This should be kept in mind when interpreting values from both models, however it is important to acknowledge that both have limitations and neither should not be considered in isolation.
7.2 Introduction

7.2.1 The Role of Workload in the Decision-Making Process

Sports science and medical staff share an essential role in prescribing an adequate training stimulus to athletes to enhance the physical qualities required to succeed at the elite level [23]. Given the importance of player availability to team success [18, 162], the training workload prescribed should 1) minimise the risk of injury, and 2) maximise the performance benefit [23]. Although high training loads have been associated with better improvements in physical performance and reduced injury risk [8], excessive workloads, and most notably spikes in workload (i.e. high acute:chronic workload ratios, ACWR > 1.5) are associated with increased injury risk [26]. It should be noted that identifying increasing risk is not necessarily predictive of injury, that is, spikes in workload (and subsequently ACWR) do not guarantee an injury, they just make it more likely [99]. Along with workload, there are multiple other factors, known as mediators or moderators of injury risk, that influence the workload and injury relationship [132]. These include but are not limited to; aerobic fitness and playing experience [108], high chronic workload [27], exposure to bouts of maximal velocity running [27], and neuromuscular and perceptual fatigue [132].

7.2.2 The Role of the Acute:Chronic Workload Ratio in Injury Prevention

Recently, a rolling averages (RA) approach has been used to calculate acute and chronic workloads, where all workload performed within a 7-day and 28-day window are considered equal, although different acute and chronic time windows have also been investigated [98, 128]. While the ACWR calculated using the rolling averages method describes periods of higher injury risk, concerns have been raised around the use of this model, because the decaying nature of fitness and fatigue over time is not considered [154]. To account for this,
an exponentially weighted moving averages (EWMA) model has been proposed. This non-linear model places greater weighting on more recent workload performed, and a decreasing weighting on older workload values [134]. Applying the EWMA model provided significantly greater sensitivity for detecting periods of increased injury risk [159]. This suggests that the EWMA model of ACWR calculation may be better suited to modelling workloads for injury risk than the RA model. However, while this possible improvement in identification of injury risk is appealing it is unclear how these models differ at a practical individual workload level.

In this paper, we identify key differences in loading patterns between the models (RA and EWMA), and discuss how spikes in workload can occur in one, or both, of the ACWR models. Three real-world examples from a professional Australian Football team using total distance as an illustrative variable are used to demonstrate the differences, and the corresponding ACWR values for individual players. While this case series only includes total distance, we suggest a multi-modal approach to modelling workload information using a range of workload variables that may include accelerations/decelerations, high- and very-high speed distance, and accelerometer load. These workload variables should also be considered with other measures of performance and recovery (i.e. wellness, heart rate, etc.). The daily workload values, along with acute and chronic workloads, and RA and EWMA ACWR calculations are explained in Table 7 and displayed in Figure 12.
Table 7. Description of differing acute and chronic workload values using the rolling averages and exponentially weighted moving averages models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolling averages</td>
<td>Acute workload</td>
<td>Sum of one-week (i.e. 7 days) total distance covered</td>
</tr>
<tr>
<td></td>
<td>Chronic workload</td>
<td>Four-week (i.e. 28 days) rolling average of acute workload</td>
</tr>
<tr>
<td></td>
<td>Acute:chronic workload ratio</td>
<td>RA acute workload / RA chronic workload</td>
</tr>
<tr>
<td>Exponentially weighted moving averages</td>
<td>Acute workload</td>
<td>$\text{EWMA}<em>{\text{today}} = \text{Load}</em>{\text{today}} \times \lambda_a + ((1 - \lambda_a) \times \text{EWMA}_{\text{yesterday}})$, where $\lambda_a = 2 / (7 + 1)$</td>
</tr>
<tr>
<td></td>
<td>Chronic workload</td>
<td>$\text{EWMA}<em>{\text{today}} = \text{Load}</em>{\text{today}} \times \lambda_a + ((1 - \lambda_a) \times \text{EWMA}_{\text{yesterday}})$, where $\lambda_a = 2 / (28 + 1)$</td>
</tr>
<tr>
<td></td>
<td>Acute:chronic workload ratio</td>
<td>$\text{EWMA}$ acute workload / $\text{EWMA}$ chronic workload</td>
</tr>
</tbody>
</table>

$\lambda_a$ is a value between 0 and 1 that represents the degree of decay.
The player categories were as follows;

7.3 A Player Returning from Injury

In this example (Figure 12 A), the player returned from a long-term injury and had built moderate-to-high chronic workloads through an individualised rehabilitation on-ground running program. During the second week, four on-ground running- and football-based training sessions were completed with lighter workloads performed earlier in the week and a large session towards the end, to replicate the typical loading pattern during an in-season week. Following the workload on day 14, this player experienced a EWMA ACWR value of 1.53 and a RA ACWR value of 1.42. Due to the spike in EWMA ACWR, the player was de-loaded the following week to mitigate his risk of injury with lighter training sessions on days 17, 18, and 20. Since the player ‘tolerated’ this spike in workload, he returned to moderate-high workloads. The increase in workload during the fourth week, particularly on day 28, resulted in a EWMA ACWR value of 1.55, while the RA ACWR value was 1.25 on the same day. Using the RA ACWR model, this player fell within the ‘sweet spot’ of workload [9], while the EWMA ACWR model returned a resultant ‘spike’ in ACWR. This highlights a key difference between the models, where the EWMA model increases due to a large workload, and is indicative of the workload that the player has failed to perform in the recent short-term.

7.4 A Player Who Plays Regularly, But Doesn’t Train Consistently

This player (Figure 12B) participated in modified and therefore inconsistent and reduced training due to a chronic condition, and competed regularly in matches. If moderate-to-high chronic training workloads minimise the risk of injury [9, 17], then this player was considered an ‘at-risk’ player. This player was considered imperative to team success, and
was managed by decreasing training workload during the week to enable him to play. While it is important for this player to play, this style of management, and consequent loading pattern may be detrimental for two reasons; 1) the slowly decreasing chronic workload decreases the amount of workload that this player ‘tolerated safely’ [16], and 2) the lower chronic workload increased the number of ‘spikes’ in workload this player encountered. In both instances, the risk of subsequent injury is increased [9, 16, 17]. This player does not leave the ‘sweet spot’ of RA ACWR for the duration of the period [9], ranging from 0.35 – 1.26. However, when considered using the EWMA model, this player experienced an ACWR value of > 1.5 on days 14 and 21. While no injury occurred immediately, the risk for this player was increased in the subsequent week [9]. Consequently, this player sustained a soft-tissue injury during the next match on day 28. This example highlights four key points; 1) spikes in EWMA ACWR can be attributed to training that this player had not completed over a period of time, 2) the EWMA model is more sensitive to acute changes in workload relative to the previous short-term workload performed, 3) it supports the premise that there is a delayed increase in injury risk following a spike in workload, and 4) low chronic workloads are also associated with increases in injury risk. The management of a player in this scenario should be considered on an individual and context-specific basis. However some possible practical strategies to minimise the risk of injury for a player in this scenario are; 1) pre-loading of workload during periods with more time between matches to allow for greater training workload without compromising recovery between matches, and 2) building of training workload in a controlled environment away from the main training group to minimise the risk of injury through controlled prescription of workload.
7.5 A Player with a Consistent Playing and Training Schedule

This player (Figure 12C) participated in full training, and competed regularly in matches during the in-season period. His loading pattern followed a consistent trend where three football-based sessions and a match were completed each week. Across this period, the values for chronic workload (range 20,368 – 25,199 m), RA ACWR (range 0.77 – 1.25), and EWMA ACWR (range 0.78 – 1.42) remained within acceptable ranges. This player maintained moderate-to-high chronic workload, which made it difficult to spike workload and subsequently the ACWR, using either model [17]. Although no spikes (ACWR > 1.5) occurred during this 28-day period, there was a trend whereby each time a match was played, ACWR values using the EWMA model would increase, while the RA model remained constant. This highlights a potential limitation of the EWMA model, as the greater emphasis on the short-term load may fail to truly account for the chronic workload developed over the period prior to a given day, due to the decay factor applied to the workload. This example highlights three points; 1) when using the EWMA model, players in consistent training can experience large increases in workload, and subsequently large increases in ACWR, 2) while a ‘spike’ in EWMA ACWR may occur, it should be considered in combination with other factors (e.g. previous injury history, physical fitness, biomechanical deficiencies) which may also contribute to injury risk [26], and 3) while the EWMA model places a greater weighting on the workload performed within an acute time period, practitioners should still consider chronic workload as measured using rolling averages, along with spikes in ACWR using the EWMA model to gauge an athlete’s preparedness to tolerate a given workload.
Figure 12. Daily workloads, along with acute and chronic total distance, and two models of ACWR calculation (RA & EWMA) of three individual players over a 28-day period. Daily load = the total distance completed on a given day. Acute load = rolling 7-day average. Chronic load = 28-day rolling average. RA ACWR = acute:chronic workload ratio using the rolling averages model. EWMA ACWR = acute:chronic workload ratio using the exponentially weighted moving averages model. * represent spikes (i.e. ACWR > 1.5) in EWMA ACWR.
7.6 Practical Applications

By providing more evidence around the different models of ACWR calculation, and the strengths and weaknesses of each model (Table 8), this better informs sports science and medical staff to ‘safely’ prescribe training loads to enhance physical qualities, whilst also minimising the risk of workload-related injury. We suggest that in relation to injury risk, acute and chronic workload data should be independently modelled using the RA model to gain a meaningful understanding of actual workloads. Using case example C as an illustrative example, on day 28, this player had a chronic workload of 25,199 m, and an acute workload of 25,698 m. In comparison, the EWMA model returned an acute workload of 5,407 m, and a chronic workload of 3,897 m, which is difficult to interpret comparatively due to the nature of the equation (Table 9). While differences do exist between the calculation of the models, and the subsequent values generated, it is important to note that there are circumstances when the values generated are similar (i.e. days 17 and 19). In this example, of 84 ACWR observations (n = 28 days for each player), 25 observations (29.9%) were within 0.1. For interpretation of the ACWR we suggest the use of the EWMA model due to the greater sensitivity to increases in injury likelihood, when considering decisions surrounding workload.

7.7 Conclusions

This case series aimed to identify and examine the loading patterns of three arbitrarily chosen players to provide some examples of common loading patterns faced in professional sport. In this case we chose: a player returning from injury, a player who plays regularly but doesn’t train consistently, and a player who plays and trains consistently. The loading patterns of each player were examined using two methods of ACWR calculation, namely the rolling averages and exponentially weighted moving average methods. While the EWMA method
has shown increased sensitivity when considering injury likelihood [159], both models offer some value in quantifying a given workload for a given player [151, 159]. The key difference between the models is that the EWMA model places a greater weighting on the more recent workload performed, which better fits with basic physiological principles [154], whereas the RA model treats all workload over a given period as equal. It is important to acknowledge that there are limitations with both models, and further work should be conducted to determine the optimal training structure, along with the corresponding ACWR values across multiple common loading patterns. It should also be made clear that neither of these models are not predictive of injury [99], but rather help gauge the preparedness of athletes and times of increased injury risk.
Table 8. Strengths and weakness of the rolling averages and exponentially weighted moving averages models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolling averages</td>
<td>• Provides an accurate indication of acute and chronic workloads performed</td>
<td>• Considers all workload completed in an acute or chronic window as equal</td>
</tr>
<tr>
<td></td>
<td>• Easy to calculate and interpret by practitioners</td>
<td>• Use of averages may overlook variations in how workload is accumulated over a period of time</td>
</tr>
<tr>
<td></td>
<td>• Moderate-to-high chronic workload, calculated using RA in isolation, offers a protective effect against injury</td>
<td></td>
</tr>
<tr>
<td>Exponentially weighted moving averages</td>
<td>• Provides a more sensitive indicator of injury likelihood than RA</td>
<td>• Acute and chronic workload values difficult to interpret in isolation due to decay factor, and do not provide a true indication of workload performed</td>
</tr>
<tr>
<td></td>
<td>• Accounts for decaying nature of fitness and fatigue over time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Places a greater weighting on the more short-term workload performed (i.e. fatigue)</td>
<td>• Fails to account for the chronic workload period prior to a given day, and its potential positive effect on fitness</td>
</tr>
</tbody>
</table>

RA = rolling averages. EWMA = exponentially weighted moving averages.
Table 9. Calculations for acute and chronic workloads, along with the acute:chronic workload ratio using rolling averages and exponentially weighted moving averages for a selected time period for case series example C.

<table>
<thead>
<tr>
<th>Day</th>
<th>Workload (m)</th>
<th>Acute Workload (m) RA</th>
<th>Acute Workload (m) EWMA</th>
<th>Chronic Workload (m) RA</th>
<th>Chronic Workload (m) EWMA</th>
<th>ACWR RA</th>
<th>ACWR EWMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>3817</td>
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RA = rolling averages. EWMA = exponentially weighted moving averages. ACWR = acute:chronic workload ratio.
Chapter 8

Study 6 – Reducing spikes in workload and building chronic workload decreases injury rate and burden in elite Australian football players

This study has been submitted for publication in the Br J Sports Med.
8.1 Abstract

**Objective:** Low chronic workload and acute spikes in workload have been associated with higher injury rates. However, no study has investigated the effect of building chronic workload and minimising spikes in workload on injury rate in professional sport. This study determined the effect of a training monitoring system using the acute:chronic workload ratio (ACWR) on injury incidence.

**Methods:** Eighty-one professional Australian football players participated in this 4-year study. Global positioning system technology was used to quantify workloads during training and competition. The ACWR was calculated for multiple variables (total distance, high- and very-high speed distance, and Player Load™), and soft-tissue “time-loss” injuries were recorded. To assess the effect of intervention on injury rates, the first three seasons were used to ascertain possible risk factors. The final season was used as an intervention where differences in workload, and number of “spikes” in workload (defined as ACWR > 1.5) were analysed using a two-way (training phase [pre-season vs. in-season] x season [1, 2, 3, vs. 4] repeated measures ANOVA. Injury rates were expressed as injuries per 1,000 hours while injury burden was calculated as days lost per injury per 1,000 hours, with differences calculated using the chi-squared statistic. Subjective wellness data was collected daily, with differences between seasons calculated using a one-way ANOVA.

**Results:** There was a significant increase in chronic workload for total distance during the in-season period during the 2017 season, when compared with the 2015 (p=0.001, Effect Size [ES]=1.40) and 2016 (p=0.001, ES=-1.46) seasons. Similarly, high-speed distance chronic workload was greater in 2017 than in each of 2014 (p=0.001, ES=-1.14), 2015 (p=0.001, ES=-1.09), and 2016 (p=0.084, ES=-0.47) in-season periods. Further, a significant reduction in the number of workload spikes per player during the in-season phase of the 2017 season was observed when compared with the 2014 (p=0.001), 2015 (p=0.001), and 2016 (p=0.034)
in-season periods. A significant reduction in injury rate and burden (p<0.05) was also observed across the entire 2017 season, when compared with previous seasons.

Conclusions: Appropriately staged training that builds chronic workloads in professional Australian football players, and reduces acute spikes in workload, reduces soft-tissue injury rate and burden.
8.2 Introduction

To succeed at the highest level in sport, an adequate training stimulus is required to enhance physical qualities [97]. Sports science and medical staff share an essential role in the delivery of physically hard, and appropriate training for each player at an individual level [23]. When considering decisions surrounding training load, a cost-benefit analysis has been suggested [8], where clinicians weigh up the proposed cost (i.e. injury risk) and the proposed benefit (i.e. positive physiological response) of a prescribed workload to reach an optimal cost-benefit ratio where injury risk is minimised, and performance is maximised [8]. This allows practitioners to make evidence-based decisions on the complex, and multi-factorial landscape of injury risk.

Injuries are common in elite sport [19], and player availability is seen as a key factor in the success or demise of a professional team [18, 19]. In a study of the UEFA Champions League two key findings regarding injury and performance were found: (1) professional football teams with lower injury rates had better performances in both domestic and international competition, and (2) injuries with a high burden (i.e. players lost to injury for large amounts of time) were more likely to negatively impact team performance [18]. Collision injuries are thought to be ‘largely’ unavoidable, while non-contact soft-tissue injuries are thought to be ‘largely’ preventable and associated with errors in training load, either too high or too low [20-22]. If true, sports science, medical, and coaching staff hold an important role in managing and minimising the risk of injury for players in their respective team [19, 23]. Therefore, it is crucial to understand the role of workload [9, 26, 132], and the effect of moderate-to-high chronic workload [16, 17] on the relationship between workload and injury.
Previous work in rugby league [16, 17], Australian football [24, 25, 151], Gaelic football [27, 108], soccer [111], and basketball [163] has investigated the relationship between workload and injury. A number of these studies found a significant relationship between a high acute:chronic workload ratio (ACWR) and injury risk. Recently, the use of a non-linear ‘exponentially weighted moving averages’ (EWMA) ACWR was found to be more sensitive for detecting increases in injury risk with higher ACWR values [134, 159]. While these studies hold important applications for those working in each respective sport, a common limitation is the observational nature of the research conducted. Each study modelled workload data with injury information to quantify injury risk, but none have extended their research to apply a prospective injury risk model to build chronic workloads and reduce spikes in workload, and thus reduce injury risk. Only a sole study in elite rugby league [21], modelled workload and injury data over a 2-year period to develop an injury prediction model, and then implemented that model over the following 2-year period to determine if non-contact soft-tissue injuries could be prevented [21]. They reported that in 62.3% of cases when a player was “flagged” as having the potential for injury, with no intervention undertaken, the player was subsequently injured. Although a proportion (23.6%) of incorrect predictions were made, the author suggested that the injury prediction model had greater sensitivity than the sole judgment of a coach [21].

Due to the dynamic nature of professional sport, and the multi-factorial nature of injury determinants, it is important to consider subjective information received from players along with objective information obtained from wearable technology. It is also important to consider that the application of such injury prevention models in a professional sporting environment is difficult, however, necessary to gauge the effectiveness of an injury prevention model [164]. The use of an injury prevention framework has been proposed, [164]
where the collection of baseline injury rates, identification of risk factors, application of an intervention, re-assessment of injury rates, and finally evaluation of the intervention to assess the uptake and effectiveness of the prevention is performed. To our knowledge, since the original study [21], no studies have applied an injury prevention model in a professional sporting environment. It was the aim of the present study to determine the value of developing and implementing a monitoring system using the ACWR with a specific aim of building chronic workloads and decreasing the number of workload spikes. We hypothesised that appropriate management and prescription of workloads would reduce injury rates in professional Australian football players.

8.3 Methods

8.3.1 Participants

Eighty-one players from one club competing in the Australian Football League (AFL) (age, 24.6±5.3 years; height, 188.6±8.2 cm; mass, 89.8±9.1 kg) participated in this four-year study. A total of 188 individual seasons were recorded in the present study, where 18 (22%) participants competed in all four seasons, 14 (17%) participants competed in three seasons, 25 (31%) participants competed in two seasons, and 24 (30%) participants competed in one season. Each season consisted of a 16-week pre-season period comprising running and football-based sessions, interspersed with regular weight training (~3 times per week). A subsequent 23-week in-season period followed where players typically completed 2 skill-based sessions, 2 weight sessions, and 1 match per week. The Australian Catholic University Human Research Ethics Committee approved all experimental procedures (Approval Number 2015-50E).
8.3.2 Quantifying Workloads

To quantify training and competition workloads, global positioning system (GPS) technology sampling at 10 Hz was used (Optimeye S5; Catapult Innovations, Melbourne, Australia). Along with GPS technology, the units also housed a tri-axial accelerometer, gyroscope, and magnetometer, each sampling at 100 Hz. The reliability and validity of this technology to quantify distance, velocity, acceleration, and Player Load™ has been demonstrated [40, 67]. Player Load™ was measured as a modified vector magnitude using accelerometer data from each vector (X, Y, and Z axis), and expressed as the instantaneous rate of change in each vector [67]. The external workload variables considered in the present study were chosen for consistency with previously used variables [151, 158, 159]; (1) total distance (m), (2) high-speed distance (18.0-24.0 km.hr$^{-1}$), (3) very high-speed distance (>24.0 km.hr$^{-1}$), and (4) Player Load™ (au). Using these variables, chronic workload data were calculated for each player daily, independent from EWMA ACWR calculation, using a 28-day rolling average, as previously described to gauge true workload performed in the medium term [16, 17, 151].

8.3.3 Definition of Injury

An injury was defined as any non-contact soft-tissue “time-loss” injury sustained during training or competition that resulted in a subsequent missed training session or game [24, 25]. Injury records were maintained by medical staff at the football club throughout the study.

8.3.4 Acute:Chronic Workload Ratio Calculation

The EWMA ACWR was calculated as originally described by Williams et al [134, 159]. The EWMA for a given day was calculated as;
\[ EWMA_{\text{today}} = \text{Workload}_{\text{today}} \times \lambda_a + ((1 - \lambda_a) \times EWMA_{\text{yesterday}}) \]

Where \( \lambda_a \) is a value between 0 and 1 that represents the degree of decay, with a greater weighting placed on the more recent workload performed. \( \lambda_a \) is calculated as:

\[ \lambda_a = \frac{2}{N + 1} \]

The EWMA ACWR value was calculated by dividing the EWMA acute workload by the EWMA chronic workload.

### 8.3.5 Testing the Acute:Chronic Workload Ratio Model

The present study was conducted in two phases. Firstly, workload and injury data were collected over three seasons. This data was analysed using multiple binary logistic regression (injury v. no injury) models to determine the relationship between workload and injury risk during this time period [159]. The development of this model gave insight into the relationship between workload and injury risk, and how different workloads can increase or decrease the likelihood of injury [9, 159]. Secondly, workload and injury data were collected over a fourth season in the same cohort. Based on the results from the binary logistic regression model, an injury risk model was implemented to determine if non-contact injuries could be reduced. From the model, an ACWR value of >1.5 was considered as a ‘flag’ with increased injury risk. Individual workloads were assessed daily by sports science and medical
staff, and every reasonable attempt was made to minimise the number of spikes players encountered through (1) reducing acute workloads when players neared high ACWR ranges and (2) building moderate-to-high chronic workloads through pre-loading of workloads in a given week, as it is difficult to spike ACWR from higher chronic workloads [16, 17]. Each individual injury was modelled with chronic workload and ACWR to give insight into the relationship between these variables at the time each injury occurred.

Along with workload, subjective wellness data was collected daily from players to provide information on how each player was responding to workload. Using an established monitoring system from the football club, each morning players subjectively rated their; (1) energy, (2) leg heaviness, (3) sleep quality, and (4) mental state using a 1–5 Likert scale. The ‘anchors’ used for each score were; 1 = poor, 2 = below average, 3 = average, 4 = good, 5 = very good. These values were used when considering decisions surrounding workloads for each player for a given day. Along with this, conversations with players were also included in the decision-making process, however were unable to be quantified. Taking each into account, a judgment was made daily, on each morning before workload was performed, to either decrease acute workload to minimise future spikes or continue with planned workloads. If spikes in workload occurred, the prescription of future workload was considered on an individual basis.
8.3.6 Statistical Analysis

8.3.6.1 Spikes in workload

The number of spikes in workload were counted across each season for the duration of the study, with season-to-season differences during the pre-season and in-season analysed using a two-way (training phase [pre-season vs. in-season] x season [1, 2, 3, vs. 4]) repeated measures ANOVA. Magnitude-based inferences were used to determine any practically meaningful differences between groups, along with 90% confidence intervals (CI’s) [137, 138]. Likelihoods were subsequently generated and thresholds for assigning qualitative terms to changes were assigned as follows: <1%, almost certainly not; <5%, very unlikely; <25%, unlikely; <50%, possibly not; ≥50%, possibly; ≥75%, likely; ≥95%, very likely; ≥99%, almost certainly. The magnitude of the differences between groups was considered practically meaningful when the likelihood was ≥75% [137, 138].

8.3.6.2 Workload and injury

Differences in chronic workload during the pre-season and in-season period between the 2014–2017 seasons were analysed using a two-way (phase x season) repeated measures analysis of variance (ANOVA). Individual workload and injury data were collected over three seasons and modelled using a binary logistic regression (injury v. no injury) to determine the relationship between workload and injury. The ACWR was independently modelled as the predictor variable where injury/no injury was the dependent variable. Based on the results, an injury model encompassing chronic workload measured using rolling averages, and the EWMA ACWR was determined to “flag” when players had a significantly increased risk of non-contact “time-loss” injury. All data were analysed using SPSS V.24.0 (SPSS, Chicago, Illinois, USA).
8.3.6.3 Wellness

The sum of the four subjective wellness variables was used to analyse differences across each season for the duration of the study. Data were checked for normality using a Shapiro-Wilk test. Season-to-season differences for all days, and days where workloads were spiked to an ACWR value of >1.5 were analysed using multiple one-way ANOVAs.

8.3.6.4 Injury rates

Injury rates were calculated by dividing the total number of injuries by the overall exposure hours for each season and expressed as rates per 1,000 hours of exposure, along with 95% confidence intervals. Further, injury burden was calculated as the number of days lost per 1,000 hours of exposure, along with 95% confidence intervals. The chi squared ($\chi^2$) test was used to determine significant differences across seasons.

8.4 Results

8.4.1 Differences in chronic workloads

8.4.1.1 Pre-Season

There was a significant decrease in the average chronic workload for high-speed distance in 2017, compared with 2015 (Effect Size [ES]=0.95 (90% CI 0.65 to 1.25), p=0.001, 100% Almost Certainly). Similarly, there was a significant decrease in very high-speed distance chronic workload in 2017 compared with 2014 (ES=0.89 (90% CI 0.58 to 1.20), p=0.001, 100% Almost Certainly) and 2015 (ES=1.23 (90% CI 0.96 to 1.50), p=0.001, 100% Almost Certainly). No other significant differences were reported during the pre-season phases.
Figure 13. Average chronic workloads for total distance, high-speed distance, very high-speed distance, and Player Load™ over four consecutive pre-season periods. * denotes significantly different (p<0.05) from the 2017 season.
8.4.1.2 In-Season

In regard to total distance, the 2017 in-season phase was significantly higher than both the 2014 (ES=−1.40 (90% CI -1.65 to -1.16), p=0.001, 100% Almost Certainly) and 2015 in-season phases (ES=−1.46 (90% CI -1.70 to -1.23), p=0.001, 100% Almost Certainly). Similarly, chronic workload for high-speed distance was significantly greater in 2017 than in both the 2014 (ES=−1.14 (90% CI -1.43 to -0.86), p=0.001, 100% Almost Certainly) and 2015 (ES=−1.09 (90% CI -1.37 to -0.80), p=0.001, 100% Almost Certainly) seasons, and practically greater during 2016 (ES=−0.47 (90% CI -0.81 to -0.13), p=0.084, 91% Likely). Player Load™ was also greater during the 2017 in-season when compared with 2014 (ES=−0.79 (90% CI -1.11 to -0.47), p=0.001, 100% Almost Certainly), 2015 (ES=−1.08 (90% CI -1.37 to -0.79), p=0.001, 100% Almost Certainly), and 2016 (ES=−0.42 (90% CI -0.75 to -0.08), p=0.087, 85% Likely). No differences were observed across seasons for very high-speed distance.
Figure 14. Average chronic workloads for total distance, high-speed distance, very high-speed distance, and Player Load™ over four consecutive in-season periods. * denotes significantly different (p<0.05) from the 2017 season.
8.4.1.3 Entire Season

When considered across the entire season, chronic workload for total distance was significantly greater during the 2017 season when compared with both 2014 (ES=-1.31 (90% CI -1.57 to -1.05), p=0.001, 100% Almost Certainly) and 2015 (ES=-1.19 (90% CI -1.47 to -0.92), p=0.001, 100% Almost Certainly). Similarly, high-speed distance chronic workload was greater during the 2017 season, when compared with the 2014 season (ES=-0.88 (90% CI -1.19 to –0.57), p=0.001, 100% Almost Certainly). Player Load™ was also greater during the 2017 season when compared with both 2014 (ES=-0.57 (90% CI -0.90 to -0.24), p=0.024, 97% Very Likely) and 2015 (ES=-0.95 (90% CI -1.25 to -0.64), p=0.001, 100% Almost Certainly) seasons. Chronic workload for very high-speed distance was significantly lower during the 2017 season when compared with the 2015 season (ES=0.93 (90% CI 0.63 to 1.24), p=0.001, 100% Almost Certainly). There were no further significant differences between variables across seasons.
Figure 15. Average chronic workloads for total distance, high-speed distance, very high-speed distance, and Player Load™ over four consecutive entire season periods. * denotes significantly different (p<0.05) from the 2017 season.
8.4.2 Wellness

There were no significant differences observed across seasons for wellness variables, both on days when workloads resulted in an ACWR value of less than 1.5, or greater than 1.5.

**Figure 16.** Average wellness data over four consecutive seasons for the day of when the workload completed resulted in an ACWR value of either > 1.5 or < 1.5.
8.4.3 Spikes in workload

8.4.3.1 Pre-Season

During the pre-season phase, there were a greater number of very high-speed distance workload spikes per player during the 2017 pre-season, when compared with the 2014 (ES=-0.59 (90% CI -0.92 to -0.26), p=0.025, 97% Very Likely) and 2015 (ES=-0.39 (90% CI -0.73 to -0.06), p=0.207, 83% Likely) pre-season phases. However, there were fewer total distance (ES=0.46 (90% CI 0.13 to 0.80), p=0.108, 90% Likely) and Player Load™ (ES=0.37 (90% CI 0.04 to 0.71), p=0.267, 80% Likely) workload spikes per player during the 2017 pre-season phase, when compared with 2014. There were no other differences during the pre-season phases when compared with the 2017 season.
### Table 10

Average number of workload spikes (i.e. ACWR > 1.5) per player per season during both the pre-season and in-season periods calculated using the exponentially weighted moving averages ACWR model.

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<td>Pre-Season Total distance</td>
<td>18.0 ± 8.6</td>
<td>16.3 ± 9.0</td>
<td>14.9 ± 9.7</td>
<td>13.7 ± 9.5</td>
<td>0.46</td>
<td>90%</td>
<td>0.108</td>
<td>0.27</td>
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<td>Pre-Season High speed distance</td>
<td>19.4 ± 6.7</td>
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<td>17.0 ± 10.1</td>
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<td>Pre-Season Very high speed distance</td>
<td>15.9 ± 6.9</td>
<td><em>#</em> 17.3 ± 7.8</td>
<td><em>#</em> 21.3 ± 8.4</td>
<td><em>#</em> 20.5 ± 8.0</td>
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<td>97%</td>
<td>0.025</td>
<td>-0.39</td>
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<tr>
<td>Pre-Season Player Load™</td>
<td>17.9 ± 8.5</td>
<td><em>#</em> 16.7 ± 9.1</td>
<td>14.9 ± 9.6</td>
<td>14.4 ± 9.9</td>
<td>0.37</td>
<td>80%</td>
<td>0.267</td>
<td>0.23</td>
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<tr>
<td>In-Season Total distance</td>
<td>11.7 ± 5.5</td>
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<td>6.0 ± 5.9</td>
<td>2.7 ± 3.6</td>
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<td>In-Season High speed distance</td>
<td>12.6 ± 5.3</td>
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<td>9.3 ± 4.8</td>
<td>6.8 ± 3.1</td>
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<td>100%</td>
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<td>In-Season Very high speed distance</td>
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<td><em>#</em> 13.0 ± 4.0</td>
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<td>Pre-Season Total distance</td>
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<td>Pre-Season Very high speed distance</td>
<td>28.8 ± 9.4</td>
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<td>Pre-Season Player Load™</td>
<td>28.7 ± 10.7</td>
<td>30.9 ± 11.9</td>
<td>21.3 ± 11.6</td>
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<td>0.70</td>
<td>99%</td>
<td>0.003</td>
<td>0.82</td>
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</table>

Data are reported as mean ± SD. ACWR = acute:chronic workload ratio.

* denotes significantly different (p < 0.05) from the 2017 season.

# denotes practically meaningful difference (likelihood ≥ 75%) from the 2017 season.

The exponentially weighted moving averages ACWR model,

TABLE 10 Average number of workload spikes (i.e. ACWR > 1.5) per player per season during both the pre-season and in-season periods calculated using the exponentially weighted moving averages ACWR model.
8.4.3.2 In-Season

A significant decrease in the number of total distance workload spikes during the in-season phase was observed in the 2017 in-season when compared with the 2014 (ES=1.39 (90% CI 1.14 to 1.64), \( p=0.001 \), 100% Almost Certainly), 2015 (ES=1.38 (90% CI 1.14 to 1.63), \( p=0.001 \), 100% Almost Certainly), and 2016 (ES=0.64 (90% CI 0.31 to 0.97), \( p=0.034 \), 99% Almost Certainly) in-season phases. Similarly, there were fewer workload spikes for high-speed distance during the 2017 in-season phase, when compared with the 2014 (ES=1.12 (90% CI 0.83 to 1.41), \( p=0.001 \), 100% Almost Certainly), 2015 (ES=1.27 (90% CI 1.00 to 1.53), \( p=0.001 \), 100% Almost Certainly), and 2016 (ES=0.60 (90% CI 0.27 to 0.93), \( p=0.080 \), 98% Very Likely) in-season phases. Further, for Player Load™, a decrease in the number of workload spikes during the 2017 in-season phase, when compared with the 2014 (ES=0.93 (90% CI 0.62 to 1.23), \( p=0.001 \), 100% Almost Certainly) and 2015 (ES=1.13 (90% CI 0.85 to 1.42), \( p=0.001 \), 100% Almost Certainly) in-season phases was observed. For very high-speed distance, the 2017 in-season phase had fewer workload spikes per player than during the 2016 in-season phase (ES=0.42 (90% CI 0.09 to 0.76), \( p=0.197 \), 86% Likely), however no differences were observed between 2017 and both 2014 and 2015.

8.4.3.3 Entire Season

When considered across the entire season there was a decrease in the number of total distance workload spikes during the 2017 season when compared with 2014 (ES=1.06 (90% CI 0.77 to 1.35), \( p=0.001 \), 100% Almost Certainly), 2015 (ES=1.05 (90% CI 0.76 to 1.34), \( p=0.001 \), 100% Almost Certainly), and 2016 (ES=0.39 (90% CI 0.06 to 0.73), \( p=0.216 \), 83% Likely) seasons. Further, there were fewer workload spikes for high-speed distance during the entire 2017 season, when compared with the 2014 (ES=0.77 (90% CI 0.46 to 1.09), \( p=0.001 \), 100%
Almost Certainly), and 2015 (ES=0.66 (90% CI 0.33 to 0.98), p=0.004, 99% Very Likely) seasons. For Player Load™, the 2017 season had fewer workload spikes than both the 2014 (ES=0.70 (90% CI 0.38 to 1.02), p=0.003, 99% Very Likely) and 2015 (ES=0.82 (90% CI 0.51 to 1.13), p=0.001, 100% Almost Certainly) seasons. In contrast, there were a greater amount of very high-speed distance workload spikes during the 2017 season when compared with 2014 (ES=-0.49 (90% CI -0.82 to -0.15), p=0.093, 92% Likely), but not 2015 or 2016. There were no other significant differences between workload spikes between seasons.

8.4.4 Injury Rates and Burden

Across the four-year period, 77 non-contact soft-tissue injuries were recorded where the most common sites of injury were the hamstring (42%), quadriiceps (23%), and calf (14%). The calculated injury rates and injury burden are displayed in Figure 3. Injury rates for the entire 2017 (1.89 [95% CI 0.72 to 3.06] injuries/1,000 hours) season were significantly lower p<0.05), than the 2014 (4.10 [95% CI 2.26 to 5.94] injuries/1,000 hours), 2015 (4.60 [95% CI 2.63 to 6.57] injuries/1,000 hours), and 2016 (5.41 [95% CI 3.21 to 7.21] injuries/1,000 hours) seasons. Although there was a trend towards a decrease in injury rate during the pre-season (p>0.05) and in-season (p>0.05) phases individually, no significant differences were found. With respect to injury burden, there was a significant reduction (p<0.05) during the 2017 (34.43 [95% CI 29.42 to 39.42] injury days lost/1,000 hours) season compared with 2014 (93.21 [95% CI 84.42 to 102.00] injury days lost/1,000 hours), 2015 (133.60 [95% CI 122.99 to 144.20] injury days lost/1,000 hours), and 2016 (155.15 [95% CI 144.22 to 166.08] injury days lost/1,000 hours) seasons.
Figure 17. Injury rates and injury burden, expressed per 1,000 exposure hours, across the duration of the four years for (A) pre-season, (B) in-season, and (C) the whole season. * denotes significantly different (p<0.05) from the previous seasons.
8.5 Discussion

This study investigated the application of the ACWR in a professional Australian football team over a four-year period. We collected workload and injury data through the 2014 to 2016 seasons, and applied a monitoring system in the final season (2017). Based on previous findings [16, 17] that low chronic workloads and spikes in workload are associated with greater injury risk, we aimed to build chronic workloads and minimise the number of spikes in workload in an attempt to decrease injury rates. A significant decrease in the number of workload spikes per player during the final season of the study. This was coupled with a significant increase in chronic workload for total distance, high-speed distance, and Player Load™ when compared with earlier seasons (2014 and 2015). Most notably, a significant reduction in injury rates and injury burden during the final season of the study, demonstrating that the use of the ACWR in a monitoring system can aid injury reduction.

The completion of greater amounts of pre-season training has been associated with a lower in-season injury risk across multiple sports [15, 159]. To achieve this, the systematic application of moderate-to-high workloads is required to elicit positive physiological adaptations [9]. In the present study, during the pre-season period, chronic workload was lower for high-speed distance during the final season than in 2014. Similarly, very high-speed distance chronic workload during the final season was lower than in the 2014 and 2015 pre-season periods. There were no other significant differences in chronic workload during the pre-season periods amongst the seasons. Although workloads were lower, importantly, there were only minor differences in the number of workload spikes per player during the final season. This suggests that (1) practitioners are more likely to accept an increased injury risk (through a spike in workload) when the benefit of the workload (i.e. positive physiological response) outweighs the possible negative consequence (i.e. injury), and (2) players may be
more capable of tolerating spikes in workload during the pre-season phase when there is an increased emphasis on the development of physical qualities, as opposed to an increased focus on recovery between matches during the in-season period.

We found significant increases in chronic workload for total, and high-speed distance during the final season’s in-season period, when compared with the preceding three seasons. Coupled with this, players experienced significantly fewer spikes in workload during the final season, when compared with each season prior for total distance, high-speed distance, and Player Load™. This is likely due to management strategies employed by practitioners at the football club such as (1) pre-loading of workload in weeks with longer turnaround between matches, and (2) control of training workloads between matches. Given the strength of the relationship between spikes in workload and an increased injury risk previously shown in team sport athletes [16, 17, 25, 98, 108, 111, 159], it is crucial to minimise the number of workload spikes a player is exposed to, particularly during the in-season phase. While a spike in workload may not necessarily be predictive of injury [99], the ACWR, coupled with chronic workload, is used to highlight and quantify periods of increased injury risk and to gauge an athlete’s preparedness to tolerate further workload [9]. For example, Figure 18 represents a heat map, with the strength of the heat displaying the injury risk for each given relationship between the acute:chronic workload ratio (x axis), and chronic workload (y axis). It appears that the periods of greatest risk during this study were when a player experienced a very high acute:chronic workload ratio coupled with a low chronic workload. Therefore, it may be suggested that the optimal scenario to decrease injury risk is to build and maintain moderate-to-high workloads, whilst minimising the number of spikes in workload (Figure 18).
Figure 18. A heat map displaying the injury rates for each combination of chronic workload and ACWR across the duration of the four years. Each row represents a season, while each column represents a different workload variable.
It is well understood that injuries are multi-factorial in nature, with a number of factors contributing to the workload-injury relationship [26, 132]. However, the control of workload, particularly reducing spikes in workload, has been theorised to reduce the risk of injury [9, 16, 17]. This is the first study to demonstrate that reducing the number of spikes in workload decreases the incidence of injury. Whilst daily wellness information, along with conversations with players, aided the decision making process on a practical level, there were no significant differences between seasons, and between days when workload resulted in an ACWR value of >1.5 or <1.5. The addition of other factors that influence the workload-injury relationship such as; aerobic fitness and playing experience [108], and neuromuscular and perceptual fatigue [132], may potentially increase our knowledge on the relationship between workload and injury. Although these moderators and mediators of injury risk were not included in the present study, our findings demonstrate that the use of a training monitoring system incorporating the ACWR can decrease the number of spikes in workload a player encounters, subsequently decreasing the risk of non-contact soft-tissue injury.

Although these findings hold important implications for sport science and medical staff, and while all measures were taken to ensure the real-world applicability of this study, there are some limitations that warrant discussion. First, this club experienced a large player turnover across the duration of the study period, with only 18 players involved in all four seasons. Second, there were multiple changes within the high performance, medical, and coaching departments at the football club involved in this study. These changes brought differences in training, playing, and conditioning philosophies across multiple seasons, particularly during the 2016 season, which may have altered injury rates. Third, although these results provide insight into the dose-response relationship for workload and injury, they do not provide information into the dose-response relationship between workload, fitness, and performance.
Fourth, players’ exposures to other workload stimulus during a week, outside of field sessions (i.e. weight sessions and off-legs conditioning) were not included in the present study. Fifth, given the known association between low chronic workloads [9, 16, 17], and spikes in workload [108, 111, 159] and injury risk, it is not possible to determine whether higher chronic workloads, decreases in the number of spikes in workload in the final season, or the interaction between both, had the greatest impact on the reduction in injury rates. Finally, it should be noted that in some instances, subjective information gathered through conversation between players and medical staff may have altered the training plan. This is due to the dynamic environment of football clubs, and unfortunately could not be avoided due to the nature of the applied research. Further work incorporating these internal workload variables, and larger studies across multiple players, clubs, and sports, would enhance the understanding of the relationship between workload and injury.

8.6 Conclusions

The use of a monitoring system using the ACWR was able to reduce the number of workload spikes a player encountered, increase the chronic workload performed, and reduce the injury rate of non-contact soft-tissue injuries in professional Australian football players. For the first time, this study demonstrates that a well-structured training program consisting of moderate-to-high workloads, while minimising the number of workload spikes, can decrease both injury rate and burden. Future work should continue to investigate the longitudinal outcomes of controlled training workloads on injury rates, along with the interaction of moderating variables in the workload-injury relationship.
8.7 What are the New Findings?

- A training monitoring system using the ACWR can reduce the number of workload spikes a player experiences.
- Minimising the number of large workload spikes (i.e. high ACWR values) for a range of workload variables may decrease the risk of non-contact soft-tissue injury.
- A combination of moderate-to-high chronic workload, coupled with the reduction of workload spikes resulted in the lowest injury rates, suggesting this may be the optimal scenario to decrease injury risk.

8.8 How Might this Impact on Clinical Practice in the Near Future?

- The ACWR is an evidence-based model, supported by current literature, which can be used to determine periods of increased injury risk in athletes.
- Injuries in professional sport are typically multi-factorial, with a range of factors influencing the workload-injury relationship. The use of a training monitoring system can reduce the number of workload spikes a player encounters, subsequently reducing the risk of injury.
- Practitioners should employ suitable risk management strategies in their prescription of workload, taking into account the workload athletes have performed previously, along with the workload they are expected to complete in the future. This approach provides a well-rounded training plan to enhance the physical qualities of athletes through physically hard and appropriate training, while minimising the risk of non-contact soft-tissue injury.

8.9 Acknowledgements

The authors extend their thanks to the players and staff of the Brisbane Lions Australian Football Club for their support and contribution to this study.
Chapter 9

Summary and Conclusions
9.1 Overview

This program of research investigated current methods of monitoring external training and game workloads in Australian Football, using Global Positioning System (GPS) technology, and the subsequent relationship with injury risk, to advance the current practices of workload modelling and injury risk analyses. The research first identified existing gaps in the workload-injury literature through a thorough and detailed analysis of existing research across a range of team sports. In order to strengthen the understanding of the relationship between external workload and injury risk in Australian football players, multiple studies were conducted and evidence gathered during both training and competition. A previously proposed injury risk model (the acute:chronic workload ratio) was applied, while a new model (using exponentially weighted moving averages) to quantify injury risk using external workloads was investigated. Next, absolute and relative workloads were used to quantify injury risk. In the next chapter, the practical applications of the models were discussed, along with key differences in the models and suggestions for use in the applied setting. Finally, an intervention study was performed in an attempt to decrease injury rate through the building of chronic workload and reduction of spikes in workload that players encountered.

9.2 Summary of Major Findings

Table 11 summarises the aims and findings of each of the experimental chapters:
Chapter 3
Investigate if acute and chronic running workloads, and the acute:chronic workload ratio were associated with subsequent injury risk

(i) Large spikes in acute workload will be associated with increased injury risk
(ii) An acute:chronic workload ratio > 2.0 was associated with increased injury risk

Chapter 4
Investigate the relationship between the proportion of pre-season training completed and subsequent in-season training.

A greater proportion of pre-season training completed will result in more training completed during the following in-season period.

**Findings**

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Murray NB, Cabbett TJ, and Townshend AD. The use of individualised speed zones in Australian Football: Are we really measuring workload risk in Australian football.

The use of relative workloads will be more sensitive to changes in injury likelihood. Irrespective of workload used, a very high ACWR was associated with increased injury risk. Large spikes in workload are associated

Chapter 6

Examine the differences between absolute and relative workloads, injury likelihood, and the acute:chronic workload ratio.

Relative workloads will be more sensitive to changes in injury likelihood, particularly at higher velocities. The use of relative workloads altered the amount of very high-speed running.

The exponentially weighted moving averages model will be more sensitive for detecting increases in injury likelihood using the acute:chronic workload ratio. Large spikes in workload are associated

Chapter 5

Investigable if any differences exist. The exponentially weighted moving averages model is more sensitive for detecting injury risk. Methods of acute:chronic workload ratio for detecting increased injury risk are comparable. However, the exponentially weighted moving averages model is more sensitive for detecting increased injury risk in

Chapter 4

### Table 11, Continued

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<tr>
<th>Aims</th>
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<td>Chapter 7</td>
<td>Differences will exist in loading patterns between acute:chronic workload models of the different models of acute:chronic workload ratio calculation</td>
<td>Load can occur in one or both models and differences were found in the acute:chronic workload ratio value produced using both models and exponential weighted moving averages vs. rolling averages vs. rolling averages vs. rolling averages vs. rolling averages vs. rolling averages.</td>
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Murray NB, Gabbett TJ, Townshend AD, and Blanch P. Reducing spikes and building chronic workload decreases injury rate and injury rate, season period, subsequently reducing a player encountered during the in-season period, subsequently reducing the number of workload spikes. System using for reducing injury rate, implementing a training monitoring system, determining the value of developing and implementing a training monitoring system. Submitted for publication in Br J Sports Med.

Murray NB, Gabbett TJ, Townshend AD, and Blanch P. Load and Injury in AFL. Submitted for publication in Br J Sports Med.
Expanding on this summary:

(i) In Chapter 3, it was hypothesised that large spikes in acute workload, resulting in a very high acute:chronic workload ratio would be associated with increases in injury risk. This study demonstrated that large spikes in acute running workload, both in total distance and high-speed distance, resulting in a very large acute:chronic workload ratio (i.e. > 2.0) were significantly associated with increases in injury likelihood both in the current week (relative risk [RR] = 8.65), and the subsequent week (RR = 5.49). These findings confirm previous work in cricket [14], and rugby league [16, 17], where it was reported that large spikes in acute workload, resulting in a large acute:chronic workload ratio (i.e. >2.0) were significantly associated with increased injury risk. A secondary finding in this chapter was the protective effect of moderate-to-high chronic workload; higher workloads were associated with a reduced risk of injury. This is in line with multiple recent studies [17, 27] which have also suggested a protective mechanism where higher chronic workloads may reduce the risk of injury. These findings highlight the importance of individual monitoring of acute and chronic running workloads, along with the acute:chronic workload ratio to reduce the risk of injury. The experimental hypothesis was strongly supported by the results of this study.

(ii) Chapter 4 in this program of research addressed the hypothesis that a player who completes a “good” pre-season, based on amount of training completed, would be able to maintain higher workloads during the competitive phase of the season, as well as be available to play in more matches. This study divided players into equal groups (i.e. high training, medium training, low training) based on the amount of pre-season training completed. The results demonstrated that players in the high (≥ 85% of main sessions completed) and medium (≥ 50% of main sessions completed) training groups completed a greater proportion
of in-season training sessions and were available for more matches than the low (< 50% of main sessions completed) training group. It was also shown that the relative risk of subsequent injury during the following in-season period was 1.9 times greater for the low training group compared to the high training group. These findings confirm previous work in rugby league [15], which reported that greater amounts of pre-season training completed resulted in a decreased injury risk during the in-season phase. Specifically, completing an additional 10 pre-season training sessions resulted in a 17% reduction in the odds of injury during the subsequent week. Together these findings demonstrate the importance of maximising participation during the pre-season phase to minimise injury risk during the following in-season phase. Therefore, the experimental hypothesis was also strongly supported by the results of the study.

(iii) Chapter 5 examined the hypothesis that an exponentially weighted moving averages method of calculating the acute:chronic workload ratio would provide a more sensitive indicator of injury likelihood than the previously used rolling averages model. While both models demonstrated a significant association between a very large acute:chronic workload ratio (i.e. > 2.0) and an increase in injury likelihood, the exponentially weighted moving averages method of acute:chronic workload ratio calculation provided a more sensitive indicator. It was previously suggested that unlike an exponentially weighted moving average model, a rolling averages model may not adequately account for the decaying nature of fitness and fatigue over time [134]. While the exponentially weighted moving averages method provided greater sensitivity for the acute:chronic workload ratio, the notion that large spikes in acute workload relative to the chronic workload (i.e. a high acute:chronic workload ratio) increased injury risk – irrespective of the calculation method used, remains. It was concluded that the acute:chronic workload ratio calculated using the exponentially weighted
moving averages model, is more sensitive, thus the experimental hypothesis was also supported by the findings of the study.

(iv) In Chapter 6, it was hypothesised that individualised workloads, calculated relative to an individual’s capacity, would be more sensitive to changes in injury likelihood, particularly for workloads at higher velocities. This study found that significant differences existed between workloads calculated using an absolute speed threshold and a relative speed threshold, but only for players within the faster and slower groups. That is, faster players demonstrated an over-estimation of high-speed running when an absolute threshold was applied, while slower players demonstrated an under-estimation of high-speed running when a relative threshold was applied. This particular finding is in line with previous work in rugby union [76], that reported significant differences in forwards and backs when individualised speed thresholds were applied. Slower players experienced increases in injury risk when greater amounts of (1) relative very high-speed running, and (2) absolute high-speed running workloads were performed. As previously shown [14, 16, 17, 108, 127], and as reported in the present study, large spikes in acute workload (i.e. ACWR > 2.0) for faster players resulted in an increased risk of injury calculated using absolute (RR = 10.31) and relative (RR = 4.28) workloads. A further finding for slower players was that greater absolute chronic workloads resulted in an increased injury risk (RR = 2.28), while greater relative chronic workloads resulted in a decreased injury risk (RR = 0.33). This finding is in partial agreement with previous studies, which suggest that higher chronic workload may offer a protective effect against injury [17, 27]. Consequently, the experimental hypothesis was only partially supported and was dependent on the variable and number of injuries included in the study.
Chapter 7 presented a case series exploring the differences in loading patterns between acute:chronic workload ratio calculation methods (i.e. rolling average and exponentially weighted moving average) and how differences can occur between these methods. It was hypothesised that despite similar loading patterns, differences would exist in the values produced using both methods of acute:chronic workload calculation. It was shown that the two methods of acute:chronic workload ratio calculation resulted in different values for the same given workload. In some cases, the exponentially weighted moving average model resulted in a ‘spike’ in workload, due to the increased weighting placed on more short-term workload completed. On the same given day, it is possible for the rolling average model to produce an acute:chronic workload ratio value within the ‘sweet spot’ of workload [9]. These differences occur due to the size in workload performed, along with the timeframe in which it is performed within a given window of time (i.e. 28 days). This finding holds important implications for the application of one or both models in an applied setting. However, in some instances, the values produced from both models will be similar. This finding suggests that the values produced from these calculations should not be considered in isolation, but rather in context with chronic workload performed [9, 17, 27]. Thus, the hypothesis was supported by the results presented in this study.

Chapter 8 examined the application of a training monitoring system to reduce the number of spikes in workload, and subsequently injury rate over the course of an Australian Football League (AFL) season. The relationship between the acute:chronic workload ratio and injury risk was established over three seasons (2014-2016). In the final season (2017), the number of spikes in workload were reduced and injury rates compared with the three preceding seasons. A significant reduction in the number of spikes in workload for total distance during the in-season phase was observed during the 2017 season when compared
with the 2014 (p = 0.001), 2015 (p = 0.001), and 2016 (p = 0.034) seasons. Similar decreases in the number of workload spikes were observed for high-speed distance and player load during the 2017 in-season phase. Further, there were significant increases in chronic workload for total distance across the entire 2017 season when compared with both the 2014 (p = 0.001) and 2015 (p = 0.001) seasons. Similarly, high-speed distance chronic workload was greater across the entire 2017 season than the 2014 (p = 0.001) season. Given the known association between spikes in workload and increases in injury risk [9, 14, 16, 17, 127, 128, 151, 159], and higher chronic workloads and decreases in injury risk [17, 27, 122, 151], it was suggested that decreasing the spikes in workload and maintaining moderate-to-high chronic workload would decrease the rate of injury. The findings of the present study demonstrated a significant (p = 0.012) decrease in injury rate and burden across the 2017 season, which supports the notion that decreasing the number of spikes in workload, and increasing chronic workload, may subsequently decrease the risk of injury [9, 133, 152]. Therefore, the hypothesis of the study was supported by the findings of the study.

Figure 19 displays a schematic diagram summarising the major findings of each experimental chapter:
Figure 19: A schematic diagram displaying the relationship between acute and chronic workload, the ACWR, player availability, and injury risk in professional Australian football.
9.3 Points of Difference

This program of research advances current understanding of the relationship between workload and injury, and provides practical outcomes for measuring workload and quantifying injury risk in elite Australian footballers.

The points of difference made by this program of research are:

(i) The designed research program strengthened the level of evidence around the need to monitor external workload in elite Australian footballers. The literature review highlighted the importance of the relationship between workload and injury, and the strength of the association between a previously used workload model (i.e. acute:chronic workload ratio) and increases in injury likelihood across a range of sports. While the importance of monitoring workload in relation to injury risk has been previously documented, the majority of research has failed to account for the workload for which a player is prepared. The idea that a player’s risk of injury increases significantly when they are required to perform a significantly greater amount of work (i.e. acute workload) than what they have been exposed to in the previous medium-term (i.e. chronic workload), resulting in a spike in workload, is presented and explored in this thesis.

(ii) This thesis is the first to use the acute:chronic workload ratio to quantify the relationship between workload and injury in elite Australian football. Further, this thesis is the first to investigate a newly proposed method (i.e. exponentially weighted moving averages) of acute:chronic workload ratio calculation – along with a comparison between the originally proposed, and newly proposed models. While the methodology of calculation was altered, the general principle that large spikes in acute workload are associated with increases in injury risk, irrespective of the model used, remained the same.
(iii) Current methodologies of workload modelling in relation to injury risk have been 1) difficult to interpret and apply successfully in a practical environment, and 2) retrospective in nature resulting in a limited capacity to alter an outcome. This program of research has provided information on the practical application of workload modelling, along with real-world examples of elite Australian football players (provided in chapter 7). Further, this research has demonstrated the relationship between workload and injury (in chapters 3 and 5), and examined the success of an intervention using this workload model in an applied environment (in chapter 8).

9.4 Strengths

The strengths of this program of research are summarised as:

(i) Advancing the current understanding of the relationship between workload and injury in elite Australian footballers.

(ii) Investigating a representative population of professional players within the sport of Australian football provides real-world applications for those involved in the physical preparation of professional players.

(iii) Confirming the findings of previous work in different sports within AF, along with providing a new workload and injury model, which can be applied to a range of sports.

(iv) Providing novel ways to quantify workload (i.e. relative workload, and the acute:chronic workload ratio calculated using the exponentially weighted moving average method) and injury risk in elite Australian football players.
9.5 Limitations

A limitation of the research presented in this thesis is that the sample size of each study is limited to a cohort of players from one professional team competing in the Australian Football League. As such, these findings may be representative of this group of players, at this given point of time, under the particular training and conditioning philosophies of the coaching and medical staff. Although these studies provide information on the relationship between workload and injury in a cohort of elite Australian footballers, clearly larger studies involving players from multiple clubs, and potentially multiple sports, would strengthen the present findings.

Secondly, the nature of an injury is largely multifactorial and typically a result of the amalgamation of multiple aspects of training or competition. While this thesis aimed to examine the influence of running workload on injury risk, there are many areas that may contribute to injury risk which have not been included in the thesis. Some of these areas include; quality and quantity of strength training, physical strength, core stability and muscle activation, and proprioceptive demands of movement. Further work should include information on these elements of training and their influence on the workload and injury relationship.

A further limitation lies in the absence of internal workload measures throughout the series of studies presented in the thesis. While the quantification of external workload is important, the internal response within individuals may differ and may be important to consider in the relationship between workload and injury. Internal workload was excluded in this series of research, as the team studied did not collect these measures. It is suggested that in future
work, the inclusion of internal workloads, wellness information, and data on physical qualities be included in the analysis of the relationship between workload and injury.

9.6 Future Directions

The advancements in the monitoring of workload in relation to injury risk presented in this thesis have provided opportunity to further examine the relationship between workload and injury in more depth. More specifically some possible future directions for researchers working in the applied field are:

(i) This thesis provides a new framework on the ability to quantify injury risk and the relationship between workload and injury. The findings challenge previously held views on workload and injury, and offer a novel and effective method to monitor workload at an individual player level. However, this research requires further work across multiple cohorts of players to confirm and extend the findings presented in this thesis.

(ii) The relationship between workload and injury is multi-factorial in nature, and the capacity to incorporate internal workloads, along with fatigue markers, and predisposing risk factors should be considered when modelling the relationship between workload and injury in future work.

(iii) An intervention study that aimed to decrease injury rate through building chronic workload and reducing the number of spikes in workload each player encountered during a season found that injury rate can be reduced through the control, and systematic application of workload. Future work should consider closely the relationship between chronic workload and the acute:chronic workload ratio to determine if there is an optimal loading pattern to reduce injury rate. Expanding on this, the loading patterns and the relationship between
chronic workload and acute:chronic workload ratio should be examine for different injuries to determine if there are tissue-specific loading patterns to reduce the risk of non-contact soft-tissue injury rate.

(iv) There may be value in the quantification of external workload using an individualised approach to reduce the risk of non-contact soft-tissue injury rate. These findings demonstrate a difference in workload calculation for faster and slower players, and injury risk, however future research should aim to examine the optimal way to individualise the approach to workload calculation (i.e. maximal aerobic speed, maximal velocity, etc.) and the subsequent effect on injury risk.

(v) The use of wearable technology has become commonplace in professional sporting organisations, and is becoming more common at a community level. The methods of quantifying workload and injury risk presented in this thesis provide a framework that can be used across a range of sports, and may provide opportunity for greater scope of player management across a range of sporting organisations and levels. The continued use of wearable technology by players competing in all levels of competition is vital to further advance of the workload and injury area.

9.7 Practical Applications

The findings in the thesis hold important implications for current workload monitoring practices in Australian Football. While the use of wearable technology is now commonplace in professional sport, the findings of this thesis advance the use of information from these devices beyond the simple observations and routinely used GPS variables. Modelling workload in the manner presented in this thesis allows practitioners to quantify the injury risk from a given external workload, based on the previous workload to which an individual
player has been exposed. This information can be easily produced, analysed, and presented, to provide information that can readily inform decisions surrounding workload for a given player.

These findings suggest that the best approach to decrease the risk of workload-related injury is to safely build moderate-to-high chronic workloads whilst minimising the number and magnitude of spikes in workload due to large increases in acute workload. The pre-season is seen as an important time to build chronic workload, while also developing the physical qualities required to succeed at the highest level. Although the way workload is modelled may develop and advance over time, the general notion that a player should not do more than they are prepared for remains the same.

9.8 Conclusions

This thesis advanced understanding of the dynamic, and ever-changing relationship between workload and injury in professional Australian football players. The physical demands of Australian football are increasing, and the use of microtechnology to quantify player workloads in relation to injury risk is a crucial aspect of load and risk management. This thesis provides multiple novel ways to quantify the relationship between workload and injury risk in Australian football players.

This thesis supports previous literature identifying that large spikes in workload are significantly associated with increases in injury risk. Whilst we know that the cause of non-contact soft-tissue is largely multi-factorial, decisions surrounding workload are crucial to the mitigation of injury risk for a given player at a given time point. This thesis has begun to
explore the quantification of the relationship between workload and injury in professional Australian football through the use of the acute:chronic workload ratio. The way in which workload is modelled to quantify injury risk will evolve over time as demonstrated in this thesis, however the premise of the acute:chronic workload ratio should remain the same; a player completing more workload than what they are prepared for results in a significant increase in injury risk. This thesis demonstrates that there are numerous ways to quantify the workload and injury relationship, and that no one method in isolation should be used. Decisions regarding workload management should be one part of a multi-dimensional approach to quantify and minimise injury risk in professional Australian football players.
References


159. Murray NB, Gabbett TJ, Townshend AD, Blanch P. Calculating acute:chronic workload ratios using exponentially weighted moving averages provides a more


Appendices
Appendix A – Evidence of Publications

Chapter 3 – Murray NB, Gabbett TJ, Townshend AD, Hulin BT, and McLellan CP.


Individual and combined effects of acute and chronic running loads on injury risk in elite Australian footballers

N. B. Murray¹, T. J. Gabbett¹,², A. D. Townshend³, B. T. Hulin³, C. P. McLellan⁴

¹School of Exercise Science, Australian Catholic University, Brisbane, Queensland, Australia; ²School of Human Movement Studies, The University of Queensland, Brisbane, Queensland, Australia; ³Centre for Human and Applied Physiology, School of Medicine, University of Wollongong, Wollongong, New South Wales, Australia; ⁴Institute of Health and Sport, Bond University, Gold Coast, Queensland, Australia

Corresponding author: Mr. Nick B. Murray, School of Exercise Science, Australian Catholic University, Brisbane 4014, Australia. Tel: 0403 873 856, Fax: +617 3623 7630, E-mail: nicholas.murray@myacu.edu.au

Accepted for publication 23 May 2016

A model that takes into account the current workload, and the workload the athlete has been prepared for, as an acute:chronic workload ratio has been previously used as a novel way to monitor training load and injury risk. Fifty-nine elite Australian football players from one club participated in this 2-year study. Global Positioning System technology was used to provide information on running workloads of players. An injury was defined as any non-contact “time-loss” injury. One-week (acute), along with 4-week (chronic) workloads were calculated for a range of variables. The size of the acute workload in relation to the chronic workload was calculated as an acute:chronic workload ratio. An acute:chronic workload ratio of >2.0 for total distance during the in-season was associated with a 5 to 8-fold greater injury risk in the current [relative risk (RR) = 8.65, \( P = 0.001 \)] and subsequent week (RR = 5.49, \( P = 0.016 \)). Players with a high-speed distance acute:chronic workload ratio of >2.0 were 5-11 times more likely to sustain an injury in the current (RR = 11.62, \( P = 0.006 \)) and subsequent week (RR = 5.10, \( P = 0.014 \)). These findings demonstrate that sharp increases in running workload increase the likelihood of injury in both the week the workload is performed, and the subsequent week.

Relationship Between Preseason Training Load and In-Season Availability in Elite Australian Football Players

Nick B. Murray, Tim J. Gabbett, and Andrew D. Townshend

**Objectives:** To investigate the relationship between the proportion of preseason training sessions completed and load and injury during the ensuing Australian Football League season. **Design:** Single-cohort, observational study. **Methods:** Forty-six elite male Australian football players from 1 club participated. Players were divided into 3 equal groups based on the amount of preseason training completed (high [HTL], >85% sessions completed; medium [MTL], 50–85% sessions completed; and low [LTL], <50% sessions completed). Global positioning system (GPS) technology was used to record training and game loads, with all injuries recorded and classified by club medical staff. Differences between groups were analyzed using a 2-way (group × training/competition phase) repeated-measures ANOVA, along with magnitude-based inferences. Injury incidence was expressed as injuries per 1000 h. **Results:** The HTL and MTL groups completed a greater proportion of in-season training sessions (81.1% and 74.2%) and matches (76.7% and 76.1%) than the LTL (56.9% and 52.7%) group. Total distance and player load were significantly greater during the first half of the in-season period for the HTL (\(P = .03, \text{ES} = 0.88\)) and MTL (\(P = .02, \text{ES} = 0.93\)) groups than the LTL group. The relative risk of injury for the LTL group (26.8/1000 h) was 1.9 times greater than that for the HTL group (14.2/1000 h) (\(\chi^2 = 3.48, df = 2, P = .17\)). **Conclusions:** Completing a greater proportion of preseason training resulted in higher training loads and greater participation in training and competition during the competitive phase of the season.

**Keywords:** GPS, competition, injury

The Use of Relative Speed Zones in Australian Football:
Are We Really Measuring What We Think We Are?

Nick B. Murray, Tim J. Gabbett, and Andrew D. Townshend

Objectives: To examine the difference between absolute and relative workloads, injury likelihood, and the acute:chronic workload ratio (ACWR) in elite Australian football. Design: Single-cohort, observational study. Methods: Forty-five elite Australian football players from 1 club participated. Running workloads of players were tracked using Global Positioning System technology and were categorized using either (1) absolute, predefined speed thresholds or (2) relative, individualized speed thresholds. Players were divided into 3 equal groups based on maximum velocity: (1) faster, (2) moderate, or (3) slower. One- and 4-wk workloads were calculated, along with the ACWR. Injuries were recorded if they were noncontact in nature and resulted in “time loss.” Results: Faster players demonstrated a significant overestimation of very high-speed running (HSR) when compared with their relative thresholds (P = .01; effect size = -.73). Similarly, slower players demonstrated an underestimation of high- (P = .06; effect size = .55) and very-high-speed (P = .01; effect size = 1.16) running when compared with their relative thresholds. For slower players, (1) greater amounts of relative very HSR had a greater risk of injury than less (relative risk [RR] = 8.30; P = .04) and (2) greater absolute high-speed chronic workloads demonstrated an increase in injury likelihood (RR = 2.28; P = .16), whereas greater relative high-speed chronic workloads offered a decrease in injury likelihood (RR = 0.33; P = .11). Faster players with a very-high-speed ACWR of >2.0 had a greater risk of injury than those between 0.49 and 0.99 for both absolute (RR = 10.31; P = .09) and relative (RR = 4.28; P = .13) workloads. Conclusions: The individualization of velocity thresholds significantly alters the amount of very HSR performed and should be considered in the prescription of training load.

Keywords: GPS, training, physical performance, sport
Appendix B – Information Letters and Consent Forms

Chapters 3, 5, 7, & 8

Information Letter

PROJECT TITLE: Acute and chronic running loads and injury risk in elite Australian Football players

PRINCIPAL SUPERVISOR: Dr. Tim J. Gabbett

STUDENT RESEARCHER: Mr. Nicholas B. Murray

STUDENT’S DEGREE: Doctor of Philosophy (PhD)

Dear Participant,

You are invited to participate in the research project described below.

What is the project about?
The research project plans to investigate acute and chronic running loads and injury risk in elite Australian Football players. The main purpose of this study is to determine if a relationship exists between acute and chronic running loads and subsequent risk of injury.

Who is undertaking the project?
This project is being conducted by Nicholas Murray and will form the basis for the degree of Doctor of Philosophy at Australian Catholic University under the supervision of Dr. Tim Gabbett.

Are there any risks associated with participating in this project?
There are no foreseeable risks from participating in this research project, as players will not be asked to perform more than their current training and match workload.

What will I be asked to do?
As a participant in this study, you will be asked to wear a GPS unit during both training and competition. The GPS units are small matchbox sized units, which will be placed between your shoulder blades in a custom-made vest worn under the shirt during training, or in a padded compartment in the back of your jersey during competition. In addition, you will be asked to report any injuries sustained in training or competition to the Brisbane Lions Football Club staff. You will not be asked to do anything outside of what is current practice at the Brisbane Lions Football Club.

How much time will the project take?
The study will have minimal inconvenience on your preparation with all of the data already a part of the normal screening and monitoring procedures undertaken by the Brisbane Lions Football Club staff. Testing will occur at all scheduled training and during competition.

Nick Murray
Load and Injury in AFL
matches. It will take roughly one (1) minute to be set up with a GPS unit for each session/match, with a further five (5) minutes following each session/match for injury reporting with the Brisbane Lions Football Club staff. It is possible that you may be asked to attend training sessions up to 15min prior to commencement to participate in data collection.

**What are the benefits of the research project?**

Benefits from participating in this research project include enhanced and comprehensive workload management and analysis.

**Can I withdraw from the study?**

Participation in this study is completely voluntary. You are not under any obligation to participate. If you agree to participate, you can withdraw from the study at any time without adverse consequences and your personal research data will be removed from the research project if you choose to do withdraw.

**Will anyone else know the results of the project?**

Confidentiality will be protected throughout the duration of this study. All data will be coded and de-identified so there is no way anyone other than the researcher/s are able to identify you.

**Will I be able to find out the results of the project?**

Players will be provided with their individual results (if requested), and are encouraged to share these with their coaches for the purpose of injury prevention and performance improvement. All data will be stored at the ACU campus in Brisbane and destroyed in the appropriate manner as governed by the university policies.

**Who do I contact if I have questions about the project?**

Any questions regarding the project should be directed to the Principal Investigator and the Student Researcher.

**Names and Titles:** Dr. Tim J. Gabbett & Mr. Nicholas B. Murray
**Telephone Numbers:** (07) 3623 7589 & 0403 873 856
**School:** Exercise Science (Brisbane)
**Campus Address:** 1100 Nudgee Road, Banyo, QLD, 4014

**What if I have a complaint or any concerns?**

The study has been reviewed by the Human Research Ethics Committee at Australian Catholic University. If you have any complaints or concerns about the conduct of the project, you may write to the Manager of the Human Research Ethics Committee care of the Office of the Deputy Vice Chancellor (Research).

Manager, Ethics
c/o Office of the Deputy Vice Chancellor (Research)
Australian Catholic University
North Sydney Campus
PO Box 968
NORTH SYDNEY, NSW 2059
Ph.: 02 9739 2519
Fax: 02 9739 2870
Email: resethics.manager@acu.edu.au

Nick Murray
*Load and Injury in AFL*
Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

*I want to participate! How do I sign up?*
If you agree to participate in this study, you should sign both copies of the *Consent Form*, retain one copy for your own records and return the other copy to either the Principal Investigator or Student Researcher.

Yours sincerely,

Dr. Tim J. Gabbett  
Principal Supervisor

Mr. Nicholas B. Murray  
Student Researcher
Consent Form

TITLE OF PROJECT: Acute and chronic running loads and injury risk in elite Australian Football players

PRINCIPAL SUPERVISOR: Dr. Tim J. Gabbett

STUDENT RESEARCHER: Mr. Nicholas B. Murray

I …………………………………………………. (the participant) have read (or, where appropriate, have had read to me) and understood the information provided to me in the Participant Information Letter. Any questions I have asked have been answered to my satisfaction. I realise and understand that I can withdraw my consent at any time without any adverse consequences. I understand that research data collected for the project may be published or provided to other researchers in a form that does not identify me in any way. I agree that results may be shared amongst coaches for player analysis purposes.

By signing this consent form, I understand and agree to participate in this research project. I agree that:

• I may be contacted by the researchers;
• Data collection will include wearing a GPS unit during training and competition;
• Testing will require one (1) minute of preparation during training and competition, and I may be asked to arrive fifteen (15) minutes early to training on testing days;
• Injury reporting will occur following each training session and competition and will require five (5) minutes after each session;
• Data collected for the study may be published or provided to other researchers in a form that does not identify me in any way.

NAME OF PARTICIPANT: ……………………………………………………………………………………………………………………………

SIGNATURE: ……………………………………… DATE: ……………………………

SIGNATURE OF PRINCIPAL SUPERVISOR: ……………………………………………

DATE: ……………………………

SIGNATURE OF STUDENT RESEARCHER: ……………………………………………

DATE: ……………………………
Chapter 4

Information Letter

PROJECT TITLE: Does a ‘good’ pre-season equal a ‘good’ season: implications for load and injury

PRINCIPAL SUPERVISOR: Dr. Tim J. Gabbett

STUDENT RESEARCHER: Mr. Nicholas B. Murray

STUDENT’S DEGREE: Doctor of Philosophy (PhD)

Dear Participant,

You are invited to participate in the research project described below.

What is the project about?
The research project plans to investigate the relationship between a ‘good’ pre-season as determined by sessions completed and running workloads and injury during the following season. The main purpose of this study is to determine if a relationship exists between the amount of pre-season completed and the relationship between workload and subsequent injury risk during the following season.

Who is undertaking the project?
This project is being conducted by Nicholas Murray and will form the basis for the degree of Doctor of Philosophy at Australian Catholic University under the supervision of Dr. Tim Gabbett.

Are there any risks associated with participating in this project?
There are no foreseeable risks from participating in this research project, as players will not be asked to perform more than their current training and match workload.

What will I be asked to do?
As a participant in this study, you will be asked to wear a GPS unit during both training and competition. The GPS units are small matchbox sized units, which will be placed between your shoulder blades in a custom-made vest worn under the shirt during training, or in a padded compartment in the back of your jersey during competition. In addition, you will be asked to report any injuries sustained in training or competition to the Brisbane Lions Football Club staff. You will not be asked to do anything outside of what is current practice at the Brisbane Lions Football Club.

How much time will the project take?
The study will have minimal inconvenience on your preparation with all of the data already a part of the normal screening and monitoring procedures undertaken by the Brisbane Lions Football Club staff. Testing will occur at all scheduled training and during competition matches. It will take roughly one (1) minute to be set up with a GPS unit for each
session/match, with a further five (5) minutes following each session/match for injury reporting with the Brisbane Lions Football Club staff. It is possible that you may be asked to attend training sessions up to 15min prior to commencement to participate in data collection.

What are the benefits of the research project?
Benefits from participating in this research project include enhanced and comprehensive workload management and analysis.

Can I withdraw from the study?
Participation in this study is completely voluntary. You are not under any obligation to participate. If you agree to participate, you can withdraw from the study at any time without adverse consequences, and your individual data will be removed from the study.

Will anyone else know the results of the project?
Confidentiality will be protected throughout the duration of this study. All data will be coded and de-identified so there is no way anyone other than the researcher/s are able to identify you.

Will I be able to find out the results of the project?
Players will be provided with their individual results (if requested), and are encouraged to share these with their coaches for the purpose of injury prevention and performance improvement. All data will be stored at the ACU campus in Brisbane and destroyed in the appropriate manner as governed by the university policies.

Who do I contact if I have questions about the project?
Any questions regarding the project should be directed to the Principal Investigator and the Student Researcher.

Names and Titles: Dr. Tim J. Gabbett & Mr. Nicholas B. Murray
Telephone Numbers: (07) 3623 7589 & 0403 873 856
School: Exercise Science (Brisbane)
Campus Address: 1100 Nudgee Road, Banyo, QLD, 4014

What if I have a complaint or any concerns?
The study has been reviewed by the Human Research Ethics Committee at Australian Catholic University. If you have any complaints or concerns about the conduct of the project, you may write to the Manager of the Human Research Ethics Committee care of the Office of the Deputy Vice Chancellor (Research).

Manager, Ethics
c/o Office of the Deputy Vice Chancellor (Research)
Australian Catholic University
North Sydney Campus
PO Box 968
NORTH SYDNEY, NSW 2059
Ph.: 02 9739 2519
Fax: 02 9739 2870
Email: resethics.manager@acu.edu.au

Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

Nick Murray
Load and Injury in AFL
I want to participate! How do I sign up?
If you agree to participate in this study, you should sign both copies of the Consent Form, retain one copy for your own records and return the other copy to either the Principal Investigator or Student Researcher.

Yours sincerely,

Dr. Tim J. Gabbett  
Principal Supervisor

Mr. Nicholas B. Murray  
Student Researcher
Consent Form

TITLE OF PROJECT: Does a ‘good’ pre-season equal a ‘good’ season: implications for load and injury

PRINCIPAL SUPERVISOR: Dr. Tim J. Gabbett

STUDENT RESEARCHER: Mr. Nicholas B. Murray

I ………………………………………………………… (the participant) have read (or, where appropriate, have had read to me) and understood the information provided to me in the Participant Information Letter. Any questions I have asked have been answered to my satisfaction. I realise and understand that I can withdraw my consent at any time without any adverse consequences. I understand that research data collected for the project may be published or provided to other researchers in a form that does not identify me in any way. I agree that results may be shared amongst coaches for player analysis purposes.

By signing this consent form, I understand and agree to participate in this research project. I agree that;

☐ I may be contacted by the researchers;
☐ Data collection will include wearing a GPS unit during training and competition;
☐ Testing will require one (1) minute of preparation during training and competition, and I may be asked to arrive fifteen (15) minutes early to training on testing days;
☐ Injury reporting will occur following each training session and competition and will require five (5) minutes after each session;
☐ Data collected for the study may be published or provided to other researchers in a form that does not identify me in any way.

NAME OF PARTICIPANT: ………………………………………………………………………………………………………

SIGNATURE: …………………………………… DATE: ……………………………

SIGNATURE OF PRINCIPAL SUPERVISOR: …………………………………………………………………………………. DATE: ……………………………

SIGNATURE OF STUDENT RESEARCHER: ………………………………………………………………………………….. DATE: ……………………………
Chapter 6

Information Letter

PROJECT TITLE: The use of individualised speed thresholds in Australian Football: Are we really measuring what we say we are?

PRINCIPAL SUPERVISOR: Dr. Tim J. Gabbett

STUDENT RESEARCHER: Mr. Nicholas B. Murray

STUDENT’S DEGREE: Doctor of Philosophy (PhD)

Dear Participant,

You are invited to participate in the research project described below.

What is the project about?
The research project plans to investigate the use of individualised speed zones compared with currently used absolute speed thresholds. The main purpose of this study is to compare and contrast the individualisation of speed thresholds to determine if any differences in individual training and match workloads exist once an individual speed threshold is applied.

Who is undertaking the project?
This project is being conducted by Nicholas Murray and will form the basis for the degree of Doctor of Philosophy at Australian Catholic University under the supervision of Dr. Tim Gabbett.

Are there any risks associated with participating in this project?
There are no foreseeable risks from participating in this research project, as players will not be asked to perform more than their current training and match workload.

What will I be asked to do?
As a participant in this study, you will be asked to wear a GPS unit during both training and competition. The GPS units are small matchbox sized units, which will be placed between your shoulder blades in a custom-made vest worn under the shirt during training, or in a padded compartment in the back of your jersey during competition. In addition, you will be asked to report any injuries sustained in training or competition to the Brisbane Lions Football Club staff. You will not be asked to do anything outside of what is current practice at the Brisbane Lions Football Club.

How much time will the project take?
The study will have minimal inconvenience on your preparation with all of the data already a part of the normal screening and monitoring procedures undertaken by the Brisbane Lions Football Club staff. Testing will occur at all scheduled training and during competition matches. It will take roughly one (1) minute to be set up with a GPS unit for each session/match, with a further five (5) minutes following each session/match for injury
reporting with the Brisbane Lions Football Club staff. It is possible that you may be asked to attend training sessions up to 15min prior to commencement to participate in data collection.

What are the benefits of the research project?
Benefits from participating in this research project include enhanced, comprehensive, and individualised workload management and analysis.

Can I withdraw from the study?
Participation in this study is completely voluntary. You are not under any obligation to participate. If you agree to participate, you can withdraw from the study at any time up until the finalisation of results for publication without adverse consequences, and your individual data will be removed from the study.

Will anyone else know the results of the project?
Confidentiality will be protected throughout the duration of this study. All data will be coded and de-identified so there is no way anyone other than the researcher/s are able to identify you, this includes club officials and coaches.

Will I be able to find out the results of the project?
Players will be provided with their individual results (if requested), and are encouraged to share these with their coaches for the purpose of injury prevention and performance improvement. All data will be stored at the ACU campus in Brisbane and destroyed in the appropriate manner as governed by the university policies.

Who do I contact if I have questions about the project?
Any questions regarding the project should be directed to the Principal Investigator and the Student Researcher.

Names and Titles: Dr. Tim J. Gabbett & Mr. Nicholas B. Murray
Telephone Numbers: (07) 3623 7589 & 0403 873 856
School: Exercise Science (Brisbane)
Campus Address: 1100 Nudgee Road, Banyo, QLD, 4014

What if I have a complaint or any concerns?
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Manager, Ethics
c/o Office of the Deputy Vice Chancellor (Research)
Australian Catholic University
North Sydney Campus
PO Box 968
NORTH SYDNEY, NSW 2059
Ph.: 02 9739 2519
Fax: 02 9739 2870
Email: resethics.manager@acu.edu.au

Nick Murray
Load and Injury in AFL
Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

_I want to participate! How do I sign up?_
If you agree to participate in this study, you should sign both copies of the Consent Form, retain one copy for your own records and return the other copy to either the Principal Investigator or Student Researcher.

Yours sincerely,

Dr. Tim J. Gabbett  
Principal Supervisor

Mr. Nicholas B. Murray  
Student Researcher
Consent Form

TITLE OF PROJECT: The use of individualised speed thresholds in Australian Football: Are we really measuring what we say we are?

PRINCIPAL SUPERVISOR: Dr. Tim J. Gabbett

STUDENT RESEARCHER: Mr. Nicholas B. Murray

I …………………………………………………………… (the participant) have read (or, where appropriate, have had read to me) and understood the information provided to me in the Participant Information Letter. Any questions I have asked have been answered to my satisfaction. I realise and understand that I can withdraw my consent at any time up until the finalisation of results for publication without any adverse consequences. I understand that research data collected for the project may be published or provided to other researchers in a form that does not identify me in any way. I agree that results may be shared amongst coaches for player analysis purposes.

By signing this consent form, I understand and agree to participate in this research project. I agree that:

☐ I may be contacted by the researchers;
☐ Data collection will include wearing a GPS unit during training and competition;
☐ Testing will require one (1) minute of preparation during training and competition, and I may be asked to arrive fifteen (15) minutes early to training on testing days;
☐ Injury reporting will occur following each training session and competition and will require five (5) minutes after each session;
☐ Data collected for the study may be published or provided to other researchers in a form that does not identify me in any way.

NAME OF PARTICIPANT: ……………………………………………………………………………………

SIGNATURE: ……………………………………… DATE: ………………………………………

SIGNATURE OF PRINCIPAL SUPERVISOR: ………………………………………………………………

DATE: ………………………………………

SIGNATURE OF STUDENT RESEARCHER: ……………………………………………………………

DATE: ………………………………………
Ethics Approval

Appendix C – Approval ID: 2015-50E

Res Ethics
2015-50E Ethics application approved!
To: Tim Gabbett, Nicholas Murray (nbmurr001@myacu.edu.au) <nbmurr001@myacu.edu.au>, Cc: Res Ethics

Dear Applicant,

Principal Investigator: Dr Timothy Gabbett
Co-Investigator: Dr Andrew Townshend
Student Researcher: Nicholas Murray (HDR student)
Ethics Register Number: 2015-50E
Project Title: Acute and chronic running loads and injury risk in elite Australian Footballers
Risk Level: Low Risk
Date Approved: 13/05/2015
Ethics Clearance End Date: 31/12/2016
Appendix D – Approval ID: 2015-182E

Res Ethics
2015-182E Ethics application approved!
To: Tim Gabbett, Nicholas Murray (nicholas.murray@mycu.edu.au) <nicholas.murray@mycu.edu.au>, Cc: Re

Dear Applicant,

Principal Investigator: Dr Timothy Gabbett
Co-Investigator: Dr Andrew Townshend
Student Researcher: Nicholas Murray (HDR student)
Ethics Register Number: 2015-182E
Project Title: Does a ‘good’ pre-season equal a ‘good’ season: implications for load and injury
Risk Level: Low Risk
Date Approved: 12/10/2015
Ethics Clearance End Date: 31/10/2016
Appendix E – Approval ID: 2016-40E

Res Ethics
2016-40E Ethics application approved!
To: Tim Gabbett, Cc: Res Ethics, Andrew Townshend, nicholas.murray@mycu.edu.au

Dear Applicant,

Principal Investigator: Dr Timothy Gabbett
Co-Investigator: Dr Andrew Townshend
Student Researcher: Nicholas Murray
Ethics Register Number: 2016-40E
Project Title: The use of individualised speed thresholds in Australian Football: Are we really measuring what we say we are measuring?
Risk Level: Low Risk
Date Approved: 02/03/2016
Ethics Clearance End Date: 31/01/2017

Nick Murray
Load and Injury in AFL