

The Response to Training and Risk of Injuries in Elite Australian Footballers

by

Alireza Esmaeili

Bachelor of Physiotherapy

Master of Clinical Exercise Practice

Thesis submitted in fulfilment of the requirements for the degree of

DOCTORATE OF PHILOSOPHY

Supervisor: Professor Andrew M. Stewart

Co-supervisor: Professor Robert J. Aughey

Co-supervisor: Dr. George P. Elias

Statistical Analysis Advisor: Professor William G. Hopkins



College of Sport and Exercise Science

Institute for Health and Sport (IHES)

2018

Abstract

Training is the systematic application of stress and recovery. The process of striking a balance between stress and recovery is facilitated by monitoring the stress dose (training load) and the response to the applied stress. This thesis investigated several musculoskeletal adaptations in response to training as well as the individual and combined effects of several athlete-monitoring-derived factors on the risk of injury in elite Australian footballers.

The first study evaluated the influence of individual internal and external training load and leg dominance on changes in the Achilles and patellar tendon structure. The internal structure of the Achilles and patellar tendons of both lower limbs of 26 elite Australian footballers was assessed using ultrasound tissue characterization at the beginning and the end of an 18 week pre-season. *Possibly to very likely* small increases in the proportion of aligned and intact tendon bundles occurred in the dominant Achilles (initial value 81.1%; change, $\pm 90\%$ confidence limits 1.6%, $\pm 1.0\%$), non-dominant Achilles (80.8%; 0.9%, $\pm 1.0\%$), dominant patellar (75.8%; 1.5%, $\pm 1.5\%$), and non-dominant patellar (76.8%; 2.7%, $\pm 1.4\%$) tendons. Measures of training load had inconsistent effects on changes in tendon structure; for example, there were *possibly to likely* small positive effects on the structure of the non-dominant Achilles tendon, *likely* small negative effects on the dominant Achilles tendon, and predominantly no clear effects on the patellar tendons. The small and inconsistent effects of training load are indicative of the role of recovery between tendon overloading (training)

sessions and the multivariate nature of the tendon response to load with leg dominance a possible influencing factor.

The aim of the second study was to determine the normal week-to-week variability of the sit and reach test (S&R), dorsiflexion lunge test (DLT), and adductor squeeze test (AST) scores, as well as the individual differences in variability and the effects of training load on the scores. Forty-four elite Australian rules footballers completed the weekly musculoskeletal screening tests on day two or three post-main training (pre-season) or post-match (in-season) over a 10 month season. Ratings of perceived exertion and session duration for all training sessions were used to derive various measures of training load via both simple summations and exponentially weighted moving averages. Data were analysed via linear and quadratic mixed modelling and interpreted using magnitude-based inference. Substantial small to moderate variability was found for the tests at both season phases; for example over the in-season, the normal variability $\pm 90\%$ confidence limits were as follows: S&R ± 1.01 cm, ± 0.12 ; DLT ± 0.48 cm, ± 0.06 ; AST $\pm 7.4\%$, $\pm 0.6\%$. Small individual differences in variability existed for the S&R and AST (factor standard deviations between 1.31 and 1.66). All measures of training load had trivial effects on the screening scores. A change in a test score larger than the normal variability is required to be considered a true change. Athlete monitoring and flagging systems need to account for the individual differences in variability. The S&R, DLT, and AST are not sensitive to internal training load when conducted two or three days post-training or post-match, and the scores should be interpreted cautiously when used as measures of recovery.

Study three evaluated the individual and combined effects of several athlete-monitoring-derived factors on the risk of soft-tissue non-contact injuries. A cohort of 55 elite Australian footballers was prospectively monitored over two consecutive seasons. Internal and external training load was quantified using the session rating of perceived exertion and GPS/accelerometer units, respectively. Cumulative loads and acute-to-chronic workload ratios were derived using rolling averages and exponentially weighted moving averages (smoothed loads). History of injuries in the current and previous seasons was also recorded along with professional experience, weekly musculoskeletal screening, and subjective wellness scores for individual athletes. Individual and combined effects of these variables on the risk of injury were evaluated with generalized linear mixed models. High cumulative loads and acute-to-chronic workload ratios were associated with increased risk of injuries. The effects for measures derived using exponentially weighted moving averages were greater than those for rolling averages. History of a recent injury, long-term experience at professional level, and substantial reductions in a selection of musculoskeletal screening and subjective wellness scores were also associated with increased risk. The effects of high cumulative load were underestimated by ~20% before adjusting for previous injuries, whereas the effects of high acute-to-chronic workload ratios were overestimated by 10-15%. Injury-prone players were at a more than five times higher risk of injuries compared to robust players (hazard ratio 5.4, 90% confidence limits 3.6–12). Combinations of multiple risk factors were associated with extremely large increases in risk; for example, a hazard ratio of 22 (9.7–52) was observed for the combination of high acute load, recent history of a leg injury,

and a substantial reduction in the adductor squeeze test score. This study determined that the information from athlete monitoring practices should be interpreted collectively and used as a part of the injury prevention decision-making process along with consideration of individual differences in risk.

The findings of this thesis highlight the multivariate nature of the response to training and injuries. This thesis has provided a framework for the monitoring of team sport athletes to ensure a better application of training stress and reduce the now much better understood risk of injury.

Student Declaration

I, Alireza Esmaeili, declare that the PhD thesis entitled “The Response to Training and Risk of Injuries in Elite Australian Footballers” is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

Signature:



Date: 21/2/2018

Acknowledgments

Doing a PhD was as challenging a journey as being away from my family after migrating from my home country. I would not have been able to survive this challenge if it was not for the kind help and support of many people around me.

I would like to thank my principal supervisor, Andy. You were my lecturer for the research design and statistics subject during my master's course. Your intriguing teaching approach settled my inner conflicts about doing a PhD. You helped me with various aspects of my project and gave me the confidence I needed to excel. This project would not have been possible without your hard work and support.

A huge thanks to the content expert of my project, my co-supervisor Rob. You trusted me in a sports science project even though I was from a clinical background (the dark side!). You taught me how to think for myself and make a balance between standing on my own –scientific– feet and asking for help when needed. Your insightful feedback and the tough love approach helped me grow not just as a scientist, but also as a person. You have inspired me over the past few years and I am very grateful for everything you have done for me. I will be forever in your debt. Oh and I really like your sense of humour... No kidding!

To the amazing Will Hopkins... I cannot even begin to describe how lucky I feel to have had the opportunity to learn from you. Your passion for numbers is contagious! Your work ethics and attention to detail are exemplary. You always managed to find a solution when the codes were not working and I thought I was stuck in a dead end. Sorry for all the headaches I gave you with my complicated ideas. Thank you, thank you, and thank you.

A big thanks to my co-supervisor, George. Your insightful feedback and kind words of support were so valuable. To the Western Bulldogs Football Club for giving me access to their data and facilities. To all the players and staff at the club for their support of me and their dedication to my project. You made my time at the club a wonderful and rewarding experience. Go Doggies! I want to especially thank the head physiotherapist, Chris Bell who gave me all the support, technical feedback, and detailed injury data I needed during my project. I want to thank Justin Cordy for making this collaborative project possible. To our little group at the college of sport and exercise science... Alice, Amber, Brendan, Kristal, Mat, Mick, Ramon, and Sam. Thanks for all the feedback, support, chit chats, and coffees! It has been great to have such awesome and talented guys and girls as peers and friends. To the amazing people in my life Alireza, Andrew, Aria, Armaghan, Inna, Lisa, Myrla, Saman, Shahrooz, Sina, and Wilson who gave me the energy I needed to keep going.

Last but definitely not least... To my beautiful family. Mom and dad, you set excellent examples for me to follow in life. I would not have got to where I am today if it was not for your hard work, sacrifices, love, and support. Amin and Fatemeh, you are not only my caring and loving siblings but also my best friends. Thanks for always being there for me. And to aunty Fariba for being the angel you are and helping me navigate my way in life. You guys mean the world to me and I love you all so much.

Abbreviations

| | |
|--------------------|------------------------------------|
| ACL | Anterior Cruciate Ligament |
| ACWR | Acute-to-Chronic Workload Ratio |
| AFL | Australian Football League |
| AST | Adductor Squeeze Test |
| AU | Arbitrary Units |
| CI | Confidence Interval |
| CL | Confidence Limits |
| Cm | Centimetre |
| DLT | Dorsiflexion Lunge Test |
| ES | Effect Size |
| GPS | Global Positioning System |
| HIR | High Intensity Running |
| Hz | Hertz |
| ICC | Intraclass Correlation Coefficient |
| km | Kilometres |
| km.h ⁻¹ | Kilometres per Hour |
| m.s ⁻¹ | Metres per Second |
| MBI | Magnitude-Based Inference |

| | |
|-------------|--|
| mm | Millimetre |
| mmHg | Millimetres of Mercury |
| POMS | Profile of Mood State |
| RESTQ-sport | Recovery-Stress Questionnaire for athletes |
| RPE | Rating of Perceived Exertion |
| S&R | Sit-and-Reach |
| SD | Standard Deviation |
| SEE | Standard Error of the Estimate |
| SEM | Standard Error of Measurement |
| sRPE | Session Rating of Perceived Exertion |
| UTC | Ultrasound Tissue Characterization |

Publications

The following publications in peer-reviewed journals and conference presentations are direct results of this thesis:

Publications:

1. **Esmaeili, A.**, Stewart, A. M., Hopkins, W. G., Elias, G. P., & Aughey, R. J. (2017). Effects of training load and leg dominance on Achilles and patellar tendon structure. *International Journal of Sports Physiology and Performance*, 12(Suppl 2), S2-122-126. doi: 10.1123/ijsp.2016-0397. (Study 1 – Chapter 3)
2. **Esmaeili, A.**, Stewart, A. M., Hopkins, W. G., Elias, G. P., Lazarus, B. H., Rowell, A. E., & Aughey, R. J. (2018). Normal variability of weekly musculoskeletal screening scores and the influence of training load across an Australian Football League season. *Frontiers in Physiology*, 9, 144. doi: 10.3389/fphys.2018.00144. (Study 2 – Chapter 4)
3. **Esmaeili, A.**, Hopkins, W. G., Stewart, A. M., Elias, G. P., Lazarus, B. H., & Aughey, R. J. (2018). The individual and combined effects of multiple factors on the risk of soft tissue non-contact injuries in elite team sport athletes. *Frontiers in Physiology*, 9(1280). doi: 10.3389/fphys.2018.01280. (Study 3 – Chapter 5)

Conference presentations:

1. **Esmaeili, A.**, Stewart, A. M., Hopkins, W. G., Elias, G. P., & Aughey, R. J. (2016). Positive changes in the Achilles and patellar tendon structure of

elite Australian footballers over the pre-season training period: The influence of training load and leg dominance. *The 2nd Aspire Academy Sports Science Conference, Doha, Qatar.*

2. **Esmaeili, A.**, Hopkins, W. G., Stewart, A. M., Elias, G. P., Lazarus, B. H., & Aughey, R. J. (2018). The individual and combined effects of multiple factors on the risk of soft tissue non-contact injuries in elite team sport athletes. *The 23rd annual Congress of the European College of Sports Science (ECSS), Dublin, Ireland.*

The following publications in peer-reviewed journals arose during candidature but are outside the scope of this thesis:

1. Aughey, R. J., Elias, G. P., **Esmaeili, A.**, Lazarus, B., & Stewart, A. M. (2016). Does the recent internal load and strain on players affect match outcome in elite Australian football? *Journal of Science and Medicine in Sport*, 19(2), 182-186. doi: 10.1016/j.jsams.2015.02.005
2. Lazarus, B. H., Stewart, A. M., White, K. M., Rowell, A. E., **Esmaeili, A.**, Hopkins, W. G., & Aughey, R. J. (2017). Proposal of a global training load measure predicting match performance in an elite team sport. *Frontiers in Physiology*, 8, 930. doi: 10.3389/fphys.2017.00930
3. Rowell, A. E., Aughey, R. J., Hopkins, W. G., **Esmaeili, A.**, Lazarus, B. H., & Cormack, S. J. (2018). Effects of training and competition load on neuromuscular recovery, Testosterone, Cortisol, and match performance during a season of professional football. *Frontiers in Physiology*, 9, 668. doi: 10.3389/fphys.2018.00668

Table of Contents

| | |
|--|-----------|
| Chapter 1 – Introduction | 1 |
| Chapter 2 – Review of the literature | 4 |
| 2.1 Injury risk statistics | 4 |
| 2.1.1 Risk factors and effect statistics..... | 4 |
| 2.1.2 Injury risk | 5 |
| 2.1.3 Injury rate..... | 6 |
| 2.1.4 Injury odds | 6 |
| 2.1.5 Injury hazard | 7 |
| 2.1.6 The uncertainty and interpretation | 8 |
| 2.1.7 Comparing different risk factor effect statistics | 11 |
| 2.2 Training | 13 |
| 2.2.1 Background | 13 |
| 2.2.2 Overreaching and overtraining | 14 |
| 2.2.3 Quantification of training load | 17 |
| 2.2.4 Derived measures of training load | 21 |
| 2.2.5 Training load and the risk of injury | 24 |
| 2.3 Tendon structure, response to changes in load, and the role of ultrasound imaging | 51 |
| 2.3.1 Tendon structure..... | 51 |
| 2.3.2 Tendon response to changes in load..... | 54 |
| 2.3.3 Asymmetries between the dominant and non-dominant sides..... | 57 |
| 2.3.4 The tendon pathology continuum..... | 61 |
| 2.3.5 Ultrasound imaging and the risk of developing tendinopathy symptoms..... | 63 |
| 2.3.6 Ultrasound tissue characterization (UTC) | 70 |
| 2.4 Musculoskeletal screening | 73 |
| 2.4.1 Background | 73 |
| 2.4.2 Musculoskeletal screening and the risk of injury..... | 74 |
| 2.4.3 Pre-season (pre-participation) screening versus regular screening | 83 |
| 2.5 History of previous injuries | 86 |
| 2.6 Subjective wellness | 91 |

| | | |
|---|---|-----|
| 2.7 | Age | 93 |
| 2.8 | Aims of the thesis | 96 |
| Chapter 3 – Study 1: Effects of training load and leg dominance on Achilles and patellar tendon structure | | |
| 98 | | |
| 3.1 | Introduction | 98 |
| 3.2 | Methods | 99 |
| 3.2.1 | Participants | 99 |
| 3.2.2 | Design | 100 |
| 3.2.3 | Methodology | 100 |
| 3.2.4 | Statistical analysis | 102 |
| 3.3 | Results | 102 |
| 3.4 | Discussion | 107 |
| 3.5 | Practical Applications..... | 109 |
| 3.6 | Conclusion..... | 109 |
| Chapter 4 – Study 2: Normal variability of weekly musculoskeletal screening scores and the influence of training load across an Australian Football League season..... | | |
| 111 | | |
| 4.1 | Introduction | 111 |
| 4.2 | Methods | 114 |
| 4.2.1 | Participants | 114 |
| 4.2.2 | Study design | 114 |
| 4.2.3 | Screening tests | 115 |
| 4.2.4 | Training load | 116 |
| 4.2.5 | Statistical analysis | 117 |
| 4.3 | Results | 120 |
| 4.4 | Discussion | 127 |
| 4.4.1 | Normal variability | 127 |
| 4.4.2 | Individual differences in variability | 128 |
| 4.4.3 | Effects of training load | 129 |
| 4.5 | Conclusion..... | 132 |
| Chapter 5 – Study 3: The individual and combined effects of multiple factors on the risk of soft tissue non-contact injuries in elite team sport athletes..... | | |
| 133 | | |
| 5.1 | Introduction | 133 |
| 5.2 | Methods | 135 |

| | | |
|---|---|------------|
| 5.2.1 | Participants..... | 135 |
| 5.2.2 | Seasonal structure..... | 135 |
| 5.2.3 | Injury definition and recording process | 136 |
| 5.2.4 | History of previous injuries..... | 136 |
| 5.2.5 | Training load constructs and derived measures | 137 |
| 5.2.6 | Professional experience | 138 |
| 5.2.7 | Musculoskeletal screening..... | 139 |
| 5.2.8 | Subjective wellness | 140 |
| 5.2.9 | Statistical analysis | 140 |
| 5.3 | Results | 145 |
| 5.3.1 | The individual effects | 148 |
| 5.3.2 | The adjusted and combined effects | 154 |
| 5.4 | Discussion | 159 |
| 5.4.1 | Training load..... | 159 |
| 5.4.2 | Exponentially weighted moving averages versus rolling averages | 162 |
| 5.4.3 | History of previous injuries..... | 163 |
| 5.4.4 | Professional experience | 165 |
| 5.4.5 | Musculoskeletal screening..... | 166 |
| 5.4.6 | Subjective wellness | 167 |
| 5.4.7 | The combined effects and decision-making..... | 168 |
| 5.4.8 | Limitations | 171 |
| 5.5 | Conclusion..... | 172 |
| Chapter 6 – General discussion, conclusion, and future research..... | | 173 |
| 6.1 | Introduction | 173 |
| 6.2 | Changes in tendon structure over an intensified training period and the influence of training load | 174 |
| 6.3 | Weekly musculoskeletal screening in team sports..... | 176 |
| 6.4 | The individual and combined effects of injury risk factors | 178 |
| 6.5 | Practical applications | 180 |
| 6.6 | Conclusions..... | 181 |
| Appendix A. UTC parameters and protocols | | 183 |
| References | | 184 |

List of Tables

Table 2.1. Summary of studies investigating the relationship between training load and risk of injury in elite/professional football code athletes.

Table 2.2 Comparison of the findings of studies investigating the relationship between training load and risk of injury in elite/professional football code athletes.

Table 2.3. Summary of studies investigating the differences in structural properties between the dominant and non-dominant Achilles and patellar tendons.

Table 2.4. Summary of studies investigating the relationship between ultrasound-detected tendon abnormalities and the risk of developing tendinopathy symptoms.

Table 2.5. Summary of prospective studies investigating the relationship between hamstring flexibility and the risk of hamstring injury.

Table 2.6. Summary of studies investigating the effects of previous injuries on the risk of recurrent or subsequent injuries in elite/professional football code athletes.

Table 3.1. Average weekly training load and the between-subjects variability for the period between the two ultrasound tissue characterization sessions.

Table 4.1. Correlations between simple cumulative and smoothed training loads of various periods on a given day.

Table 4.2. Statistics summarizing screening test scores for an AFL team in a pre- and in-season phase derived from parts one and two of the analysis.

Table 4.3. Effects of training load on the test scores derived from part three of the analysis.

Table 5.1. Daily mean thresholds of training load levels (quantiles) for pre-season and in-season.

Table 5.2. Individual effects of training load on the risk of injuries derived from part one of the analysis.

Table 5.3. Individual effects of history of previous injuries and professional experience on the risk of injuries derived from part one of the analysis.

Table 5.4. Individual effects of musculoskeletal screening and subjective wellness scores on the risk of injuries derived from part one of the analysis.

Table 5.5. Effects of training load adjusted for history of previous leg injuries and combined with a history of a recent leg injury derived from part two of the analysis.

Table 5.6. The adjusted and combined effects of professional experience, musculoskeletal screening, and subjective wellness on the risk of injuries derived from part three of the analysis.

List of Figures

Figure 1.1. The workload-injury aetiology model.

Figure 2.1. The relationship between athletic performance, fitness, and fatigue.

Figure 2.2. Structural organization of tendon.

Figure 2.3. Ultrasound tissue characterization (UTC) images of patellar tendon.

Figure 3.1. Tendon structure at the start and the end of pre-season.

Figure 3.2. Effects of training load on Achilles and patellar tendon structure.

Figure 4.1 Changes in screening scores with changes in training load
(cumulative 7 day, smoothed 3 day, acute:chronic ratio, strain).

Figure 4.2 Changes in screening scores with changes in training load
(cumulative 3 day, cumulative 14 day, cumulative 28 day, monotony).

Figure 4.3 Changes in screening scores with changes in training load
(smoothed 7 day, smoothed 14 day, smoothed 28 day).

Chapter 1 – Introduction

The issue of injuries to athletes is a topic of great importance in professional sports. Occurrence of injuries can negatively affect team performance and chance of success (Chamari & Bahr, 2016; Ekstrand, 2013; Hagglund et al., 2013). Lower injury burden and higher match availability are associated with higher points per league match and higher final league ranking in professional soccer (Hagglund et al., 2013). Injuries can also impose substantial direct and indirect costs to the sports clubs. A single episode of hamstring strain injury is estimated to cost more than \$A40,000 in player salaries alone for the teams participating in the Australian football league (AFL) (Hickey, Shield, Williams, & Opar, 2013). The injury costs are even higher for professional European soccer clubs where average player wages are considerably higher than in the AFL. In the highest level of European soccer, the average cost of a one-month-long injury to a first-team player is estimated to be around €500,000 (Ekstrand, 2013). Injury prevention is therefore an area of high priority in elite sports settings.

The injury causation models developed throughout the past few decades provide the basis for injury prevention practices currently adopted in professional sports (Hulme & Finch, 2015). It was initially proposed that intrinsic risk factors uniquely predispose each athlete to injury, and exposure of the predisposed athletes to external risk factors makes them susceptible to injury (Meeuwisse, 1994a). This multifactorial model of injury causation was further modified to reflect the dynamic nature of susceptibility to injury (Meeuwisse, Tyreman, Hagel, & Emery, 2007). The susceptibility of athletes to injury was proposed to continually change based

on the adaptations and maladaptations that occur following repeated sports participation (Meeuwisse et al., 2007). In a recent development of this model, “application of workload” was included as the primary process through which an athlete is exposed to extrinsic risk factors and inciting events (Figure 1.1) (Windt & Gabbett, 2017).

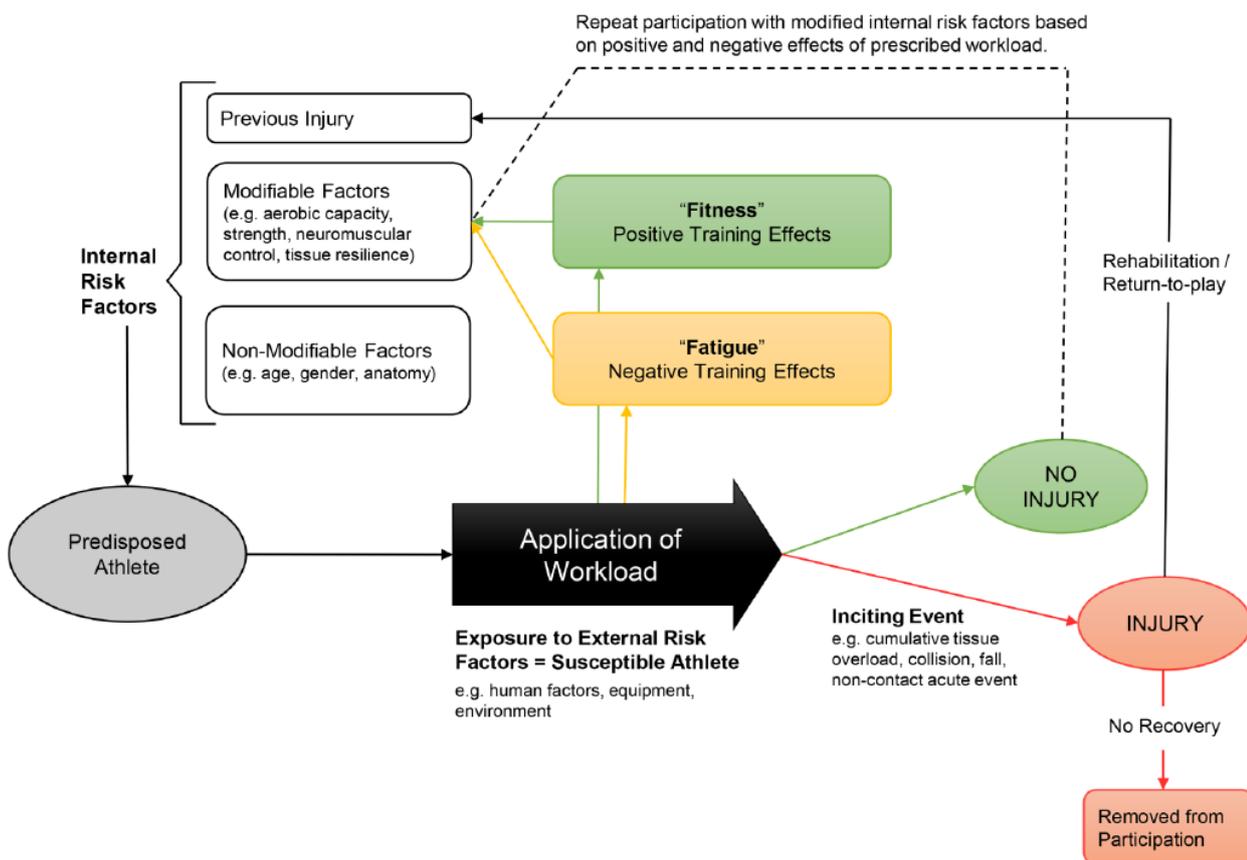


Figure 1.1. The workload-injury aetiology model. Reproduced from Windt and Gabbett (2017).

Athlete monitoring practices currently employed in elite sports settings, aim to screen the factors that affect or reflect the dynamic states of adaptation and maladaptation of athletes to training, for the two main purposes of injury prevention and performance enhancement (Akenhead & Nassis, 2016; Taylor, Chapman, Cronin, Newton, & Gill, 2012; Thorpe, Atkinson, Drust, & Gregson,

2017). These practices include monitoring training load, subjective wellness, musculoskeletal characteristics, history of previous injuries, and professional experience. The effects of these variables on the risk of injury have predominantly been evaluated in isolation, whereas injury is a multifactorial process. In addition, changes in the musculoskeletal system in response to regular sports participation have rarely been investigated.

This thesis will therefore evaluate the individual and combined effects of training load, subjective wellness, musculoskeletal screening scores, history of previous injuries, and professional experience on the risk of injury, as well as the changes in musculoskeletal system in response to training in elite Australian footballers. While the main focus of this thesis is on elite Australian rules football, evidence is drawn from other sports, in particular other football codes, when appropriate.

Chapter 2 – Review of the literature

2.1 Injury risk statistics

2.1.1 Risk factors and effect statistics

An injury risk factor is defined as a variable that is associated with the incidence of injuries, or in other words, a factor that modifies the likelihood of injury as a consequence of participating in physical activity (Hopkins, Marshall, Quarrie, & Hume, 2007). Injury risk factors are generally categorized as intrinsic and extrinsic, and each of these categories can also be subdivided into modifiable and non-modifiable risk factors (Bahr & Holme, 2003; Meeuwisse, 1994a; Van Mechelen, Hlobil, & Kemper, 1992). Intrinsic risk factors are those internal to the athlete, meaning they arise from within the athlete's body (e.g. muscular strength, history of previous injury). Extrinsic risk factors are those external to the athlete, and are usually associated with the environment, protective gear, or the rules of the sport (e.g. playing surface, use of mouth guards, the number of interchange) (Bahr & Holme, 2003; Hrysomallis, 2013; Van Mechelen et al., 1992).

Researchers use a number of injury risk statistics to quantify the effects of injury risk factors (Hopkins et al., 2007). As a general principle, athletes are first divided into an exposed group (athletes who have the risk factor of interest) and an unexposed group (athletes without the risk factor of interest). One of the injury incidence statistics (injury risk, injury rate, injury odds, or injury hazard) is then calculated for the exposed and unexposed groups. Finally, the incidence statistic of the exposed group is divided by the incidence statistic of the unexposed group to provide a ratio (risk ratio, rate ratio, odds ratio, and hazard ratio) that

summarizes the effect of that particular risk factor on the occurrence of injuries (effect statistics) (Hopkins et al., 2007). The following sections describe how each of the four commonly used injury risk statistics are calculated, and how to interpret and compare the findings of studies that have used different methods of quantifying the effects of an injury risk factor.

2.1.2 Injury risk

While injury risk is often used as a general term to refer to all injury incidence statistics, it is also a specific statistic that describes the proportion of athletes who get injured over the study period, or in other words the probability of injury for any given athlete in the studied sample (Hopkins et al., 2007). For example, the injury risk for a sample of 100 athletes where 30 athletes get injured over a season is 0.3 or 30%. The effect statistic associated with injury risk is the “risk ratio”, which is also known as relative risk. In this sample of 100 athletes, let it be assumed that 10 of 20 athletes who have a history of previous injury get injured (the exposed group; injury risk 50%) and 20 of 80 athletes who do not have the risk factor of interest get injured (the unexposed group; injury risk 25%) over the study period. The effect of history of previous injury as an injury risk factor is expressed as a risk ratio (relative risk) of 2, which means athletes with a history of previous injury are at a 2 times higher risk of getting injured compared to athletes without this risk factor over a season. The calculation of risk ratio is based on the assumption that the exposed and unexposed groups have the same amount of exposure to the sport. This assumption may not always be true, in which case directly comparing the injury incidences of the two groups is not appropriate. Injury rate is the incidence statistic that addresses this issue.

2.1.3 Injury rate

Injury rate is defined as the count of injury incidences divided by the total exposure to the sporting activity (Hopkins et al., 2007). Injury rate normalizes the number of injuries for the amount of sport participation which is the essential contributor to sports injuries (no sports participation results in no sports injuries). The effect statistic associated with the injury rate is rate ratio. Risk ratio and rate ratio would be the same when there are no differences between the groups with and without the risk factor of interest in their exposure to the sport. The most common way of quantifying the exposure is by measuring the amount of time spent in training and matches by individual players. For example the average injury rate of a sample can be expressed as 24 injuries per 1000 player (or exposure) hours which includes the total time spent in training sessions and competitive matches (McManus et al., 2004). A limitation of this approach is that the training and match hours are combined together, while injury rates are nearly five times higher during matches compared to training sessions (Engebretsen, Myklebust, Holme, Engebretsen, & Bahr, 2010; Hägglund, Waldén, & Ekstrand, 2006). In order to address this issue, training and match participation time can be recorded separately, and the match exposure ratio (match hours divided by the total exposure time) can be included as a covariate in the analysis (Hägglund, Waldén, & Ekstrand, 2013).

2.1.4 Injury odds

Injury odds are calculated by dividing the probability that injury will happen, by the probability that it will not happen (Hopkins et al., 2007). In the example discussed earlier, the odds ratio for the effect of history of previous injury as a

risk factor can be calculated by dividing the injury odds of the exposed group (0.5/0.5=1) by the injury odds of the unexposed group (0.25/0.75=0.33), which results in an odds ratio of 3. This odds ratio of 3 does not mean that the athletes with a history of previous injury are at a 3 times higher risk of getting injured compared to the athletes without this risk factor. They are actually at a 2 times higher risk as previously demonstrated by calculating the risk ratio. Odds ratio can be interpreted in the same way as a risk ratio only under certain circumstances which will be discussed in section 2.1.7 (comparing different risk factor effect statistics).

2.1.5 Injury hazard

Injury hazard is defined as the instantaneous injury risk per unit time (Hopkins et al., 2007). The previous methods calculate the injury risk for a relatively long period (most commonly one season), but the risk of injury incidence can be calculated for shorter periods (such as an hour of game play or a day) using injury hazard. Below is the formula for calculating the injury hazard (Verhagen & Van Mechelen, 2010):

$$\text{Injury hazard} = [- \ln (1 - \text{Injury risk})] / t$$

**ln* = natural log function **t* = time period for injury risk divided by time period for injury hazard

It is important to note that in the calculation of injury hazard, it is assumed that the hazard is consistent over the study period (the assumption of proportional hazard) (Hernán, 2010). The injury hazard approach may not be robust to violation of this assumption under certain circumstances. For example, if the risk

of a particular injury is considerably higher at the earlier or later stages of the season, calculation of injury hazard may not be appropriate.

Similar to the other methods, hazard ratio is calculated by dividing the injury hazard in the exposed group by the injury hazard in the unexposed group (Hopkins et al., 2007). The hazard ratio for the example discussed in section 2.1.2 is 2.4, which means the athletes with a history of previous injury are 2.4 times more likely to get injured at any moment compared to the athletes without this risk factor (Hopkins et al., 2007). A key advantage of using hazard ratio over other effect statistics is in studies with long follow up periods and high injury risk where eventually almost all participants from both the exposed and unexposed groups get injured or develop the negative outcome of interest. In such circumstances, the hazard ratio is still useful and informative, whereas the risk ratio approximates 1 and the odds ratio approaches infinity.

2.1.6 The uncertainty and interpretation

The effect statistics for injury risk factors are calculated for a limited sample and are only an estimate of the true value for the entire population of that cohort. Confidence limits (or interval) is used to express the uncertainty in the magnitude of the effect (Hopkins et al., 2007). The sampling uncertainty is usually presented as 95% confidence interval which represents the range within which the true population value is likely, with 95% certainty, to be found (Batterham & Hopkins, 2006). It has been argued that the 95% level is too conservative, and 90% confidence interval is a better default level, as the chances that the true population value falls below the lower limit or above the upper limit are both very unlikely, where very unlikely has been defined as less than 5% chance

(Batterham & Hopkins, 2006). The interpretation of effect magnitudes with 90% CI has acceptable error rates and trivial publication bias (Hopkins & Batterham, 2016). However, it should be considered that the definition of very unlikely is to some extent subjective, and formal research on the validation of the associated threshold is yet to be conducted. Calculation of the uncertainty of the effect statistics is more complex than the explained basic estimates and generally requires the use of statistical packages. Different statistical procedures in statistical packages produce different effect statistics; for example, logistic regression provides odds ratios, Poisson regression outputs rate ratios, and proportional hazards regression delivers hazard ratios (Hopkins et al., 2007). Calculation of the uncertainty for risk ratios is different to the other effect statistics in that instead of performing regression analysis, the normal distribution of the natural log of injury risk is used to calculate the upper and lower confidence limits (Altman, 1990). The uncertainty in the effect of a risk factor as well as the smallest practically important effect should then be used to interpret the effects of a risk factor on occurrence of injuries (Batterham & Hopkins, 2006).

A ratio of 1 for an injury risk factor effect statistic represents an equal risk of injury in the exposed and unexposed groups. A higher risk of injury in the exposed group results in a ratio greater than 1 and a lower risk of injury in the exposed group results in a ratio smaller than 1 when compared to the unexposed group. The current guidelines recommend the ratio of 1.1 as the smallest important effect for risk factors, which would result in a 10% increase in the incidence of injuries (Hopkins, Marshall, Batterham, & Hanin, 2009). The inverse of this ratio ($1/1.1=0.9$) is the smallest important protective effect of the risk factor of interest,

which would result in a 10% reduction in the incidence of injuries. An injury risk factor is considered to have a trivial effect when the ratio falls between 0.9 and 1.1 (Batterham & Hopkins, 2006; Hopkins, 2010). Based on these thresholds, three zones of negative or protective (<0.9), trivial (0.9 to 1.1), and positive or harmful (>1.1) effects of the injury risk factor could be identified. In the magnitude-based inference (MBI) approach, the placement of the observed ratio, the lower confidence limit, and the upper confidence limit over the harmful, trivial, and beneficial zones is used to interpret the effect of an injury risk factor, and is more informative than the traditional hypothesis testing approach (p value) (Batterham & Hopkins, 2006). The interpretation of the various possible combinations of such placements are explained extensively in the literature (Batterham & Hopkins, 2006) but in essence, the positive (harmful) effect of an injury risk factor is clear and practically important when the ratio is greater than 1.1 and the lower confidence limit is greater than 0.9. On the other hand, the negative (protective) effect of an injury risk factor is clear and practically important when the ratio is smaller than 0.9 and the upper confidence limit is smaller than 1.1 (Batterham & Hopkins, 2006).

While the recommended threshold of 10% change in injury risk has been used throughout this thesis, it should be acknowledged that there is a need for further discussions on whether other thresholds should be used for different types of injuries based on their occurrence rate, severity, consequences, and associated costs.

2.1.7 Comparing different risk factor effect statistics

Comparing the magnitude of findings between studies that show different effect statistics (e.g. odds ratio and risk ratio) may not be as simple as a direct comparison between the ratios. The calculated ratios in the example explained in section 2.1.2 were 2, 2.4, and 3 for risk ratio, hazard ratio, and odds ratio, respectively. In this example the odds ratio is 1.5 times larger than the risk ratio which is a considerable difference from the clinical decision making standpoint. In order to make appropriate comparisons between studies showing different effect statistics, the provided information in regards to the number of athletes and injury incidences in the exposed and unexposed groups need to be used to recalculate the effect statistic of one study as explained previously, so both ratios would be of the same nature. In the event that recalculation of the effect statistics is not possible, the proportion of the injured athletes in the sample (injury risk) determines the appropriateness of a direct comparison. The gap between the risk ratio, hazard ratio, and odds ratio increases in the same order (risk ratio < hazard ratio < odds ratio) as the proportion of injured athletes over the study period increases above 10%, and a direct comparison between different effect statistics may not be appropriate (Hopkins et al., 2007). On the other hand, the risk ratio, hazard ratio, and odds ratio are close to each other when the injury risk is less than 10%, which justifies a direct comparison when recalculation of the effect statistics is not feasible. These principles have been taken into account through the remainder of this thesis in evaluation of the findings of different studies. The following sections focus on several athlete-monitoring-derived variables that are deemed to affect the risk of injury. These variables include training, tendon

structure, musculoskeletal screening, history of previous injuries, subjective wellness, and age.

2.2 Training

2.2.1 Background

Training refers to a systematic application of stress with the aim of improving physiological capacity and athletic performance (Meeusen et al., 2013; Morgans, Orme, Anderson, & Drust, 2014). The imposed stress on a physiological system results in stimulation of adaptive mechanisms that attempt to restore homeostasis (Fry, Morton, & Keast, 1991; Halson & Jeukendrup, 2004). The model of general adaptation syndrome describes three stages that occur following exposure of a physiological system to a stressor (Selye, 1956). The initial alarm reaction stage is characterized by a temporary reduction in the resistance of the system in response to the stressor (fatigue). The resistance stage ensues where the body's resistance increases to levels higher than the previous baseline (super-compensation). Continual exposure to the stressor beyond the adaptive capacity of the system results in a decline in resistance below the baseline levels and the stage of exhaustion.

The general adaptation theory was further developed to explain the relationship between athletic performance, fitness, and fatigue (Banister, Calvert, Savage, & Bach, 1975). It was proposed that performance is determined by the interaction between positive effects of fitness and negative effects of fatigue (Performance = Fitness – Fatigue) (Figure 2.1). A later development of the model differentiated between acute and chronic fatigue (Performance = Fitness – (chronic fatigue + acute fatigue) (Corlett, 1976). The fitness and fatigue responses to training occur at different magnitudes and rates, in that changes in fitness are smaller than changes in fatigue levels, but they last for a longer period (Borresen & Lambert,

2009). Subsequently, adequate and repeated exposure to training results in gradual accumulation of the fitness effect and improved athletic performance, provided enough recovery is allowed between training bouts for the negative effects of fatigue to subside (Fry et al., 1991). On the other hand, intensified periods of training and inadequate recovery lead to accumulation of the negative fatigue effects and development of overreaching and overtraining (Halsen & Jeukendrup, 2004; Meeusen et al., 2013).

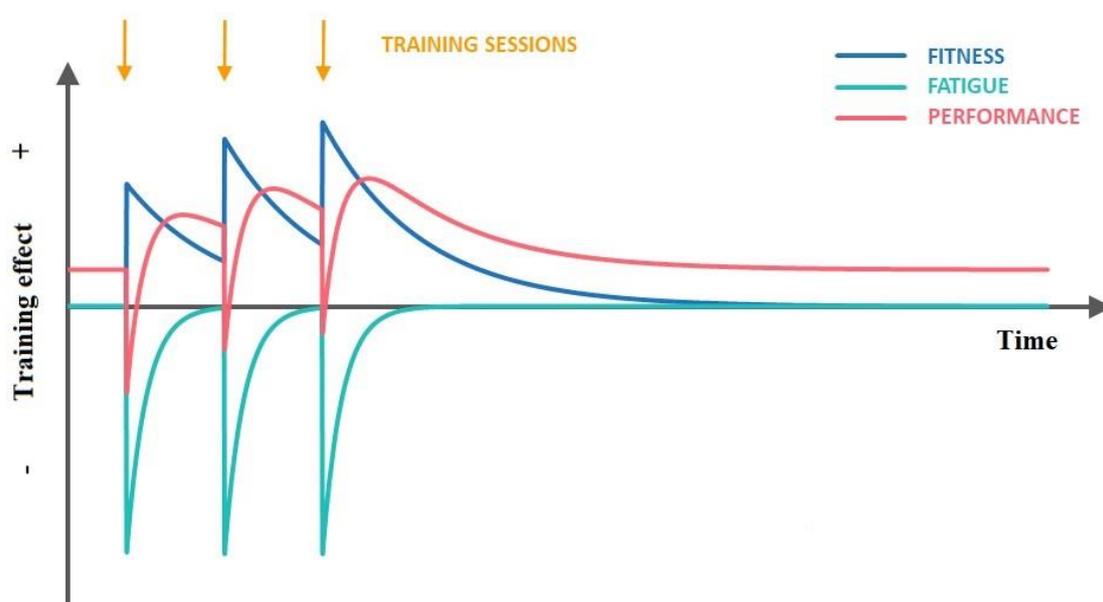


Figure 2.1. The relationship between athletic performance, fitness, and fatigue. Modified from Baldi (2017).

2.2.2 Overreaching and overtraining

Overreaching was initially defined as a short-term decline in performance resulting from an accumulation of training and/or non-training stress with or without signs and symptoms of maladaptation, where performance decrements take several days/weeks to resolve (Kreider, Fry, & O'Toole, 1998). A similar definition was proposed for overtraining, with the exception that the performance

decrements were long-term and took several weeks to several months to return back to normal (Kreider et al., 1998). These definitions limit the difference between overreaching and overtraining to the time taken for the negative performance changes to resolve, and do not take the possible accompanying signs and symptoms into account. The temporal definition limitations have at times resulted in confusion among practitioners and inappropriate use of the terms overreaching and overtraining (Budgett et al., 2000; Halson & Jeukendrup, 2004).

The European College of Sport Science and American College of Sports Medicine provided a joint consensus statement to clarify the definitions and avoid misconception of terminology in regards to overreaching and overtraining (Meeusen et al., 2013). The term overtraining is now used as a verb referring to the process of intensified training that may result in functional overreaching (short-term overreaching), non-functional overreaching (extreme overreaching), or overtraining syndrome (Halson & Jeukendrup, 2004; Meeusen et al., 2013; Urhausen & Kindermann, 2002). The process of functional overreaching is often used to enhance performance (e.g., training camps). The initial decline in performance is followed by a supercompensation effect when adequate recovery is implemented in the periodised training program (Meeusen et al., 2013; Steinacker, Lormes, Reissnecker, & Liu, 2004).

Continuation of intensified training leads to the state of non-functional overreaching, which is characterized by both a quantitative increase in training (e.g., increased training volume) and qualitative changes in the athlete (e.g., signs and symptoms of psychological or hormonal disturbances) (Meeusen et al.,

2013; Meeusen et al., 2010). The performance decline or stagnation in the non-functional overreaching state may not resume to previous levels for several weeks or months (Meeusen et al., 2013). Similar declines in performance and clinical signs and symptoms are seen in overtraining syndrome, which last for prolonged periods of more than several months (Meeusen et al., 2013). In the absence of sensitive and specific diagnostic tests, the diagnosis of overtraining syndrome may only be made retrospectively based on the time course of the maladaptations (Meeusen et al., 2013).

Overtraining syndrome and non-functional overreaching are proposed to have a prevalence of approximately 10% in endurance athletes (Raglin & Morgan, 1994). This high prevalence is believed to be exaggerated by merging incidences of functional overreaching, non-functional overreaching, and overtraining syndrome (Meeusen et al., 2013). It has been speculated that overreaching is more prevalent in team sports and explosive/power sports while overtraining syndrome is more frequent in endurance sports (Halson & Jeukendrup, 2004). However, there is currently no robust evidence to support this notion or indeed the existence of a true overtraining syndrome in football code athletes.

In summary, inadequate training fails to elicit the required physiological responses to improve performance. On the other end of the spectrum, excessive training and/or insufficient recovery lead to accumulation of fatigue and the subsequent physiological and psychological disturbances, as well as short term or long term declines in performance. The challenge for coaches and sports scientists is to prescribe just the right dose of training for individual athletes to achieve the desired outcomes. Various methods for quantification of training load

have been developed to facilitate prescription of training and evaluation of training effects on performance and risk of injury.

2.2.3 Quantification of training load

A number of variables such as intensity, duration, and frequency can be used to manipulate the dynamics of training (Smith, 2003). Training load is a function of these variables, which can be quantified through internal or external parameters (Halson, 2014; Smith, 2003). External load is the physical stimulus and amount of work completed by the athlete (Impellizzeri, Rampinini, & Marcora, 2005). The total distance covered, distance covered at various speed bands, and the total power output are examples of external training load (Aughey, 2011e; Ebert et al., 2005). Internal training load is the physiological and psychological impact of the completed work on the athlete, or in other words the internal response of the athlete to the external load (Impellizzeri et al., 2005). Heart rate, oxygen consumption, and ratings of perceived exertion are examples of internal training load (Borresen & Lambert, 2008; Foster, 1998; Jeukendrup & Diemen, 1998). External load and internal load are two different constructs and should both be monitored in order to allow coaches to determine whether the target training stimulus has been completed (external load) and how the athletes are responding to it (internal load) (Scott, Lockie, Knight, Clark, & Janse de Jonge, 2013).

Training load monitoring is now common practice in professional sports (Akenhead & Nassis, 2016; Taylor et al., 2012). A survey of 41 professional soccer clubs from three continents showed that all clubs monitor internal and external training load of individual athletes for the two main purposes of injury prevention and performance enhancement (Akenhead & Nassis, 2016). Another

survey of 55 coaches and sports scientists involved in various individual and team based high performance sports revealed that 90% of respondents implement some form of training load quantification (Taylor et al., 2012). The most important reasons for the training load monitoring practices were injury prevention (29%), monitoring the effectiveness of the training program (27%), maintaining performance (22%), and preventing overtraining (22%) (Taylor et al., 2012).

Time-motion analysis has been a popular method of quantifying external load in field sport athletes over the past few decades, and was initially performed using manual video analysis. Variables such as distance covered and speed could be derived by tracking players' movement on the field (Reilly & Thomas, 1976). The advancement of microtechnology and introduction of global positioning system (GPS) allowed for a more accurate and less labour-intensive quantification of external load (Aughey, 2011a). Global positioning systems are now commonly used in field sports to monitor the external load of individual athletes (Aughey, 2011a). Athlete movements are recorded as total distance covered during a match or training session, as well as the distance covered at different speed bands generally labelled as walking, jogging, high intensity running, and sprinting (Bradley et al., 2009; Rampinini, Coutts, Castagna, Sassi, & Impellizzeri, 2007; Varley, Fairweather, & Aughey, 2012). Developments in GPS technology including increases in sampling rate of the hardware and advancement of the GPS chipsets have resulted in substantial improvements in the validity and reliability of GPS units (Aughey, 2011a; Scott, Scott, & Kelly, 2016; Varley et al., 2012). For example, the high error rates of the 1 Hz and 5 Hz MinimaxX GPS units particularly in quantification of high speed and short distance activities were

substantially improved by introduction of the 10 Hz units (Jennings, Cormack, Coutts, Boyd, & Aughey, 2010; Varley et al., 2012). High speed and short distance activities are usually of minimal duration, and higher sampling rates (more location data points per unit of time) allow GPS units to capture these efforts more accurately which in turn results in improved validity and reliability (Coutts & Duffield, 2010; Scott et al., 2016; Varley et al., 2012). Advancements in GPS chipsets have also contributed to improvements in validity and reliability through enhanced algorithms that process the positional information (Coutts & Duffield, 2010; Varley et al., 2012). In general, GPS technology is considered a valid and reliable tool for quantification of external load in football code athletes (Aughey, 2011a; Varley et al., 2012). For example, coefficients of variation of typically less than 10% for validity and 6% for reliability have been reported for 10 Hz GPS units in evaluation of instantaneous velocity (Varley et al., 2012).

Activities such as changes of direction, tackling, bumping, and taking part in contested situations commonly occur in team sports and exert substantial load on athletes; however, these activities involve minimal displacement and are under-represented in measures derived from time-motion analysis (Boyd, Ball, & Aughey, 2013; Dawson, Hopkinson, Appleby, Stewart, & Roberts, 2004). Accelerometers are highly responsive motion sensors housed in the same unit as the GPS, which quantify the magnitude and frequency of movement in three dimensions (Boyd et al., 2013).

Accelerometers are widely used in quantification and evaluation of external load in various football codes. Accelerometers have been used to evaluate the sensitivity of neuromuscular and hormonal measures of recovery to external load

of soccer matches (Rowell, Aughey, Hopkins, Stewart, & Cormack, 2017). The influence of neuromuscular fatigue on external load of elite Australian footballers has been investigated using accelerometer units (Cormack, Mooney, Morgan, & McGuigan, 2013). Accelerometers have outperformed GPS in quantifying important differences in athlete movement during rugby union matches (Howe, Aughey, Hopkins, Stewart, & Cavanagh, 2017). Accelerometer-derived measures have also been used to evaluate the relationship between training load and risk of injury (see section 2.2.5). Player Load is the most commonly used accelerometer derived measure of external load and has been validated for use in Australian football (Boyd et al., 2013; Gastin, McLean, Spittle, & Breed, 2013).

Internal training load can be quantified using a number of objective and subjective measures. Objective measures are mostly based on heart rate and the assumption of a linear relationship between heart rate and oxygen consumption during steady state exercise (Hopkins, 1991). While objective measures are widely used in endurance sports to monitor internal training load, the non-steady-state and intermittent nature of team sports have limited the validity and application of heart rate based measures for monitoring internal training load in team sport athletes (Borresen & Lambert, 2009; Impellizzeri et al., 2005).

The session rating of perceived exertion (sRPE) is the only subjective measure of internal training load that has been widely adopted in team sports owing to being non-invasive, simple and cost-effective (Scott, Lockie, et al., 2013). The subjective rating of the overall session difficulty on a modified 0-10 Borg scale is multiplied by the session duration (in minutes) to obtain a single value

representing the internal training load of that session in arbitrary units (Foster, 1998; Foster et al., 2001; Foster et al., 1995).

The sRPE method has been used to evaluate the relationship between training load and match outcome in Australian football (Aughey, Elias, Esmaeili, Lazarus, & Stewart, 2016). The sensitivity of hormonal and subjective measures of recovery to training load has been determined using the sRPE method (Buchheit et al., 2013; Thorpe et al., 2016). The sRPE method is considered to be a valuable tool for coaches, as it can be used to guide the prescription and periodization of training in team sports (Kelly & Coutts, 2007). This method of training load quantification has also been widely used in evaluation of the relationship between training load and injury risk (see section 2.2.5). The sRPE method has been validated for quantifying training load in team sports, with moderate to very large correlations reported between sRPE load and other measures of internal and external load (Casamichana, Castellano, Calleja-Gonzalez, San Román, & Castagna, 2013; Impellizzeri, Rampinini, Coutts, Sassi, & Marcora, 2004; Scott, Black, Quinn, & Coutts, 2013).

2.2.4 Derived measures of training load

The internal and external load measures discussed in the previous section are “constructs” or “measures” of training load that allow for quantification of load for individual training sessions (Moreira et al., 2015; Williams, Trewartha, Cross, Kemp, & Stokes, 2017). These individual training loads should be analysed over given time periods to obtain “derived” or “derivative” measures of training load, in order to make meaningful inferences about their effect on performance and risk of injury (Bourdon et al., 2017; Williams, Trewartha, et al., 2017). Derived

measures of training load have been primarily categorized into absolute and relative load (Drew & Finch, 2016). Absolute load is the combined training load of a given time period, most commonly simple cumulative or rolling averages of 7, 14, 21, and 28 day load (Drew & Finch, 2016; Williams, Trewartha, et al., 2017). Relative load arises from the comparison of training load of two different time periods (Drew & Finch, 2016). The most commonly used relative load derived measures are week-to-week changes in training load expressed as a percentage, and the recent to historical load calculated as a ratio (also known as the acute-to-chronic workload ratio) (Drew & Finch, 2016; Hulin et al., 2014; Williams, Trewartha, et al., 2017).

The application of derived training load measures calculated through simple summation of daily load (such as rolling averages) has recently been a source of debate (Drew, Blanch, Purdam, & Gabbett, 2017; Menaspa, 2017a; Menaspa, 2017h; Sampson, Fullagar, & Murray, 2017). It has been argued that this approach overlooks variations in daily training load over the specified time period, and disregards the overall training load pattern (Menaspa, 2017a). In addition, simple summation of daily load over a set period ignores the physiological principle that effects of a training stimulus decline over time (Hawley, 2002; Menaspa, 2017a). For instance, in calculation of a 28 day cumulative load using this approach, the same level of importance is given to the latest training session and the one conducted four weeks ago. It has been speculated that non-linear modelling of training load may be a more appropriate method of calculating the derived measures of training load (Menaspa, 2017a; Williams, West, Cross, & Stokes, 2017).

Exponentially weighted moving average is a non-linear analysis method of deriving cumulative load that accounts for the decaying effects of training by giving more weight to more recent training sessions (Williams, West, et al., 2017). The weighting of previous training load is achieved through application of a decay factor λ (lambda) to training load of previous days/weeks (Hunter, 1986; Williams, West, et al., 2017). The exponentially weighted moving average (smoothed) load at the beginning of each day is calculated as $[\lambda \times (\text{yesterday's training load})] + [(1 - \lambda) \times \text{the smoothed load up to that point}]$ (Williams, West, et al., 2017). Evidence in support of exponentially weighted moving averages for injury prevention purposes is emerging (Murray, Gabbett, Townshend, & Blanch, 2017); however, definitive conclusions cannot yet be made on whether exponentially weighted moving averages are superior to the conventional rolling averages.

A number of other derived measures of training load also exist that are based on weekly distribution/pattern of load. Training monotony is a measure of day to day variability of training load in a given week and is calculated as the mean sRPE daily load divided by the standard deviation of the load over a week (Foster, 1998). Training strain is a measure of the overall stress of the weekly training stimulus and is calculated as the weekly sRPE load multiplied by monotony (Foster, 1998). Measures of monotony and strain have substantial associations with match success (Aughey et al., 2016), subjective fatigue (Elloumi et al., 2012), immunological stress markers (Milanez, Ramos, Okuno, Boullosa, & Nakamura, 2014), and occurrence of illness (Foster, 1998; Putlur et al., 2004). Monotony and strain are valuable measures that assist coaches in planning and periodising

training for individual athletes.(Foster et al., 2001; Gamble, 2006; Pyne et al., 2000)

To summarize, training load monitoring has become an integral part of professional sports. Various constructs of internal and external training load can be used to derive absolute or relative load measures over several time periods. The relationship between various derived measures of training load and risk of injury in professional football code athletes will be discussed in the following section.

2.2.5 Training load and the risk of injury

Training induces physiological and biomechanical stress on physiological systems and body tissues (Vanrenterghem, Nedergaard, Robinson, & Drust, 2017). Accumulation of the negative effects of physiological and biomechanical stressors through vigorous training and/or inadequate recovery results in a higher chance of failure of the adaptive mechanisms and injury (Vanrenterghem et al., 2017). This phenomenon is the basis for studies that investigate the relationship between training load and risk of injury. These studies attempt to identify derived training load measures and thresholds that are associated with a substantial increase or decrease in the risk of injury, which can in turn be used to refine training prescription and load modification practices with the ultimate aims of improving performance and reducing the incidence of injuries (Drew & Finch, 2016; Vanrenterghem et al., 2017).

Tables 2.1 and 2.2 summarise and compare the methodology and findings of studies investigating the relationship between training load and risk of injury in

elite/professional football code athletes. As a general theme for these studies, a cohort of athletes are monitored over a specific period usually ranging between one to four seasons. Training load is recorded for individual athletes using various training load constructs (e.g., total distance) to generate several derived measures of training load (e.g., 1-week cumulative load). The derived measures are then divided into multiple levels, usually ranging between two and six, along with the prospectively recorded injuries associated with them. A measure of risk statistics such as injury risk or injury odds is calculated for each level. One level (usually the lower training load level) is selected as the reference group and the effect of training load on injury risk is calculated as the injury risk of each level divided by the injury risk of the reference group and presented as a ratio. Despite the similarity of this general theme between the training load/injury risk studies, a number of methodological differences exist that could potentially affect the findings and hence make each study unique.

The participants of the studies summarised in Table 2.1 were from various football codes that are substantially different in their activity profile, training and competition schedule, and common injury mechanisms (Orchard, Seward, & Orchard, 2013b; Varley, Gabbett, & Aughey, 2014). Elite Australian footballers cover substantially greater absolute and relative (to playing time) total distance, low-intensity activity distance, high-intensity running distance, and sprinting distance compared to elite soccer and rugby league players (Varley et al., 2014). On the other hand rugby league players experience greater relative number of collisions compared to Australian footballers during competitive matches (Varley et al., 2014), and soccer players tend to play competitive matches more

frequently compared to players competing in other football codes (Orchard & Seward, 2009).

Of the 26 studies summarised in Table 2.1, 13 studies were in Australian football (Carey et al., 2017; Colby, Dawson, Heasman, Rogalski, & Gabbett, 2014; Colby, Dawson, Heasman, et al., 2017; Colby, Dawson, Peeling, et al., 2017; Duhig et al., 2016; Murray, Gabbett, Townshend, Hulin, & McLellan, 2017; Murray, Gabbett, & Townshend, 2017; Murray, Gabbett, Townshend, & Blanch, 2017; Piggott, Newton, & McGuigan, 2009; Rogalski, Dawson, Heasman, & Gabbett, 2013; Ruddy et al., 2016; Stares et al., 2018; Veugelers, Young, Fahrner, & Harvey, 2016), eight studies were in rugby league (Gabbett, 2010; Gabbett & Jenkins, 2011; Gabbett & Ullah, 2012; Hulin, Gabbett, Caputi, Lawson, & Sampson, 2016; Hulin, Gabbett, Lawson, Caputi, & Sampson, 2016; Killen, Gabbett, & Jenkins, 2010; Thornton, Delaney, Duthie, & Dascombe, 2017; Windt, Gabbett, Ferris, & Khan, 2017), two studies were in rugby union (Brooks, Fuller, Kemp, & Reddin, 2006; Cross, Williams, Trewartha, Kemp, & Stokes, 2016), and three studies were in soccer (Ehrmann, Duncan, Sindhusake, Franzsen, & Greene, 2016; Malone et al., 2017; Owen et al., 2015).

The definition of injury varied between the studies summarised in Table 2.1. The four main injury definitions used in these studies included transient, medical attention, match time-loss, and training/match time-loss injuries. Transient injuries are injuries that cause players to seek first aid or medical treatment during or after the physical activity but do not result in any training modification or loss of participation (Gabbett & Ullah, 2012; King, Gabbett, Gissane, & Hodgson,

2009). This injury definition has limited value, as these injuries do not affect player availability.

Table 2.1. Summary of studies investigating the relationship between training load and risk of injury in elite/professional football code athletes.

| Author (year) | Participants (Monitoring period) Other variables | Injury definition [Injury counts] Analysis block (Latent period) | Derived training load measures (Analysed load levels) | Findings/Comments |
|-------------------------|--|--|--|---|
| 1. Brooks et al. (2008) | 502 professional rugby union players (2 complete seasons) - | Time-loss for contact and non-contact injuries separately [1475] Weekly (1 week) | Cumulative weekly training time (5 quantiles) | High training volume (>9.1 hours/week) was not associated with an increase in incidence of injuries but was associated with higher severity of match injuries. Only training and match time was quantified and not the load. Confidence intervals or exact p-values for the effects were not reported. |
| 2. Carey et al. (2016) | 52 professional Australian football players (2 complete seasons) - | Time-loss for non-contact injuries [178] Daily (0, 2, and 5 days) | ACWR using moving average of daily load. 336 daily load combinations from 8 acute time windows (2-9 days) and 7 chronic time windows (14-35 days) for 6 load constructs (total distance, on-field sRPE, Player Load, distance-load, high speed running distance, moderate speed running distance) (Average of 7, 9, and 11 quantiles) | Players with ACWR outside the 0.8-1.2 range were at an increased risk of injury for 8 of the 336 derived measures (relative risks between 1.69 and 2.74). The 3/21 day ACWR for moderate speed running best explained the injury likelihood in matches ($R^2=0.79$). Inclusion of the 2 and 5 day latent periods did not improve the ability of the model to explain variation in the risk of injury. sRPE was only quantified for field training sessions. Observations with chronic load <2 SD below the mean were removed from the analysis which may have artificially affected the injury risk especially for the high ACWR level. Pre-season injuries were removed from parts of the analysis. Only 8 of 336 derived measures had a substantial relationship with the risk of injury which raises the suspicion of type I error. The suspicion is strengthened by the fact that all the substantial |

| | | | | |
|------------------------|--|---|--|--|
| 3. Colby et al. (2014) | 46 elite Australian football players (1 complete season) (Professional experience) | Time-loss for non-contact injuries, pre-season and in-season injuries analysed separately [134] Daily (Unspecified) | Cumulative 1-4 week load and week-to-week change in load for 6 load constructs (total distance, V1 distance, sprint distance, Force Load, Velocity Load, Relative Velocity Change Load) (3 quantiles) | <p>relative risks had a lower 95% confidence limit close to 1 representing no difference in the risk of injury.</p> <p>History of previous injuries was not accounted for.</p> <p>Pre-season: Lower risk of injury associated with moderate compared to low amounts of 3-weekly velocity load (odds ratio 0.24, 95% CI 0.06-0.92), 3-weekly sprint distance (0.23, 0.05-0.97), and week-to-week change in Relative Velocity Load (0.04, 0.004-0.40). Higher risk of injury associated with moderate compared to low amounts of 3-weekly total distance (5.49, 1.57-19.16).</p> <p>In-season: Higher risk of injury associated with high compared to low amounts of 3-weekly Force Load (2.53, 1.09-5.87) and 4-weekly RVC load (2.24, 1.06-4.77). Lower risk of injury associated with moderate and high 2-weekly V1 distance, moderate 2-weekly total distance, and moderate week-to-week change in total distance when compared to the low level (odds ratios between 0.28 and 0.49).</p> <p>Moderate amounts of training load had mostly protective effects.</p> <p>Some conflicting results existed that were not explained. This study had a strict interpretation of time-loss definition (134 non-contact injuries over one season) and did not account for history of previous injuries which could have directly affected cumulative training load and explained some of the inconsistencies.</p> |
| 4. Colby et al. (2017) | 70 elite Australian football players (4 complete seasons) (Age, history of moderate/high severity injury over the previous | Modified time-loss in pre-season (>1 week of modified training) and match time-loss during in-season for non-contact injuries [104] Periodically (Multiple periods) | Cumulative total distance and sprint distance over 8 periods (early pre-season, late pre-season, pre-competition, rounds 1-5, rounds 6-11, rounds 12-17, rounds 18-end of season) (5 levels based on z-scores) | <p>Higher risk of in-season injury associated with very high early pre-season total distance (odds ratio 3.2, 95% CI 1.3-8.5), very low late pre-season total distance (5.6, 1.4-22.8), and low pre-competition distance (6.0, 1.6-23.3) compared to the moderate training load group.</p> <p>History of previous injuries in the current season was not accounted for in the analysis.</p> |

| | season as a yes/no) | | | |
|------------------------|--|--|--|--|
| 5. Colby et al. (2017) | 70 elite Australian football players (4 in-seasons) (Professional experience, wellness, musculoskeletal screening) | Match time-loss for non-contact injuries [97] Weekly (1 week) | Cumulative 1-4 week loads, week-to-week change in load, and ACWR for 3 load constructs (total distance, sprint distance, on-field sRPE) (5 quantiles) | <p>Higher risk of injury associated with very low 3-week total distance, 4-week total distance, sprint distance ACWR, 2-week on-field sRPE, 3-week on-field sRPE, 4-week on-field sRPE, and very high sprint distance ACWR compared to the moderate load group (incidence rate ratios between 1.59 and 2.32).</p> <p>Lower risk of injury associated with very high 2-week sprint and very high 4-week sprint (incidence risk ratios 0.48 and 0.45, respectively).</p> <p>Higher risk of injury associated with the interaction between low total distance chronic load and very high ACWR (incidence rate ratio 2.60, 95%CI 1.07-6.34) as well as low on-field sRPE chronic load and low ACWR (2.52, 1.01-6.29).</p> <p>History of previous injuries was not accounted for in this study which could have substantially contributed to the relationship between low cumulative load and risk of injury.</p> |
| 6. Cross et al. (2016) | 173 professional rugby union players (1 in-season) - | Time-loss for contact and non-contact injuries [465] Weekly (1 week) | Cumulative 1-4 week load, week-to-week change in load, monotony, and strain for sRPE (4 quantiles for non-linear effects and 2-SD increase in load for linear effects) | <p>Linear effects: Higher risk of injury associated with a 2-SD increase in cumulative 1-week load (odds ratio 1.68, 95% CI 1.05-2.68) and week-to-week change in load (1.58, 0.98-2.54)</p> <p>Non-linear effects: Higher risk of injury associated with high cumulative 4-week load (1.39, 0.98-1.98) and lower risk of injury associated with moderate-high cumulative 4-week load (0.55, 0.22-1.38) compared to the low training load level.</p> <p>Contact and non-contact injuries were not differentiated.</p> <p>History of previous injuries was not accounted for.</p> |
| 7. Duhig et al. (2016) | 51 elite Australian football players (2 complete seasons) (Professional experience) | Time-loss for hamstring strain injuries [22] Weekly (1 week) | Cumulative 1-4 week load for 4 load constructs (sRPE, total distance, high-speed running distance, and acceleration/deceleration distance) standardized using z-scores | <p>Higher risk of injury associated with high 1-week (odds ratio 6.44, 95% CI 2.99-14.41), 2-week (3.06, 2.03-4.75), 3-week (2.22, 1.66-3.04), and 4-week (1.96, 1.54-2.51) high speed running distance compared to the low training load level.</p> <p>Small injury counts limited the analysed load levels to 2.</p> |

(2 quantiles from z-scores)

| | | | | |
|--------------------------------|--|---|--|--|
| 8. Ehrman et al. (2016) | 19 elite soccer players (1 complete season) - | Match time-loss for non-contact injuries [16] Daily (Nil – Injuries were pinpointed to games or training sessions) | Cumulative 1-week and 4-week load for 4 load constructs (total distance, high intensity running distance, very high intensity running distance, New Body Load, and meters per minute) including the training load on the day of injury (Pre-injury training load was compared to the seasonal averages) | Injured players had higher meters per minute in the 1-week (+9.6%) and 4-week (+7.4%) periods preceding an injury compared to their seasonal averages. Injured players had lower New Body Load in the 1-week (-15.4%) and 4-week (-9.0%) periods preceding an injury compared to their seasonal averages. Periods of high training intensity (represented by high meters per minute) and under-preparedness (represented by low New Body Load) preceded non-contact injuries. GPS units could not be worn during competitive matches and training load was estimated from pre-season matches which could undermine the validity of the analysed training load data. This could be especially problematic considering the small injury counts. Small injury counts. |
| 9. Gabbett (2010) | 91 professional rugby league players (2 complete seasons + 2 seasons for model testing) (Planned vs actual load) | Time-loss for non-contact injuries [unspecified in the first 2 seasons, 159 in the second 2 seasons] Weekly (Unclear) | Cumulative 1-week load for sRPE (2 levels of safe and unsafe load based on arbitrary thresholds for 3 season phases) | Injury likelihood was 50–80% within the training load range of 3000–5000 units over the pre-season. Load thresholds were lower (1,700–3,000 units) in the late-competition phase. Players that exceeded the training load threshold were 70 times more likely to test positive for non-contact, soft tissue injury, whereas players that did not exceed the training load threshold were injured 1/10 as often. The provided arbitrary thresholds are likely to be extreme scenarios and the confidence intervals for the relative risks are not provided. |
| 10. Gabbett and Jenkins (2011) | 79 professional rugby league players (4 complete seasons) - | Medical attention for contact and non-contact injuries separately [329 non-contact and 98 contact injuries] | Daily/session load for sRPE of various training modes (Linear correlations) | Very large correlations existed between training load and overall injury ($r = 0.82$), non-contact field injury ($r = 0.82$), and contact field injury ($r = 0.80$) rates. Large correlations existed between the field training load and overall field injury ($r = 0.68$), non-contact field injury ($r = 0.65$), and contact field injury ($r = 0.63$) rates. Large correlations existed between the strength |

| | | Correlations over the study period (Nil) | | and power training load and strength and power injury rates ($r = 0.63$). The harder rugby league players train, the more injuries they will sustain. Effects of accumulated training load over periods of >1 day and the possible non-linear effects were not explored in this study. The majority of medical attention injuries (313 of 427) did not result in any training or match time-loss. It appears that the injury definition included the common post-training minor complaints (e.g., muscle tightness) which reduces the applicability of the findings for injury prevention purposes in elite settings. |
|------------------------------|---|--|---|--|
| 11. Gabbett and Ullah (2012) | 39 elite rugby league players (1 complete season) (Injury history in the previous season) | Transient and time-loss for non-contact injuries separately [40 transient, 47 training time-loss, and 14 match time-loss injuries] Daily (Nil) | Daily/session load for 12 GPS derived variables (total distance, relative distance, very low through to very high intensity movement distance, mild/moderate/maximum acceleration distance, and repeated high intensity effort bouts) (2 levels based on arbitrary thresholds) | Higher risk of transient injury associated with very high intensity running >9 meters per session (relative risk 2.7, 95% CI 1.2-6.5). Lower risk of transient and training time-loss injuries associated with greater distances covered in mild, moderate, and maximum accelerations as well as low and very low intensity movement velocities. The absence of an association between training load and match time-loss injury is likely due to the small number of match time-loss injuries. Transient injuries do not affect player availability and the findings have limited practical implications. The influence of injury history in the current season was not accounted for in this study. Effects of accumulated training load over periods of >1 day and the possible non-linear effects were not explored in this study. |
| 12. Hulin et al. (2016) | 28 elite rugby league players (2 in-seasons) (Between-match recovery time, position, | Time-loss for contact and non-contact injuries [44] Weekly | Cumulative 1-week (acute) and 4-week rolling average (chronic) load and ACWR for total distance (6 quantiles) | Lower risk of injury associated with high acute load compared to low, moderate low, and very high acute load when between match recovery time was <7 days (relative risks between 0.13 and 0.18) |

| | | | | |
|-------------------------|--|--|--|---|
| | age, height, body mass) | (The time between a match and the next training session ~2 days) | | <p>Lower risk of injury associated with high chronic load compared to low and moderate low load when between match recovery time was <7 days (relative risks of 0.32 and 0.27, respectively).</p> <p>Higher risk of injury associated with high and very high ACWR compared to low and moderate high ACWR (relative risks between 2.88 and 5.80).</p> <p>High and very high chronic load may have a protective effect against match injuries after shorter between-match recovery periods. ACWR >1.5 are associated with a greater risk of match injury than lower acute:chronic workload ratios.</p> <p>Total distance was the only evaluated load construct.</p> <p>Contact and non-contact injuries were not differentiated.</p> <p>History of previous injuries was not accounted for.</p> |
| 13. Hulin et al. (2016) | 53 elite rugby league players (2 complete seasons) | Time-loss for contact and non-contact injuries [205] Weekly (Nil and 1 week) | Cumulative 1-week (acute) and 4-week (chronic) rolling average load and ACWR for total distance (6 levels for acute and chronic load and 7 levels for ACWR based on z-scores) | <p>Higher risk of injury associated with very high acute load compared to all other load levels in the current week (relative risks between 1.9 and 13.9).</p> <p>Higher risk of injury associated with very high ACWR compared to very low, low, moderate, and high levels in the current week (relative risks between 2.0 and 6.9).</p> <p>Higher risk of injury associated with a very high ACWR of the combined current and subsequent week compared to low, moderate low, and moderate ACWR (relative risks between 1.9 and 2.4).</p> <p>Lower risk of injury associated with a combination of high chronic load and moderate ACWR compared to the combination of low chronic load and several other ACWRs (relative risks between 0.3 and 0.7).</p> <p>Lower risk of injury associated with very low ACWR compared to all other levels in the current and subsequent week (recalculated relative risks between 0.10 and 0.48).</p> <p>Total distance was the only evaluated load construct.</p> <p>Contact and non-contact injuries were not differentiated.</p> <p>ACWRs with chronic z-scores<-2 were removed from the analysis. This was to address an inherent limitation of ACWR.</p> |

| | | | | |
|--------------------------|---|--|--|--|
| | | | | History of previous injuries was not accounted for. |
| 14. Killen et al. (2010) | 36 professional rugby league players (1 pre-season) (Subjective wellness) | Medical attention for contact and non-contact injuries [20] Correlations between weekly injury rate and weekly training load over the study period (Nil) | Cumulative 1-week load, monotony, and strain for sRPE (Linear correlations) | <p>No substantial relationships between weekly injury rate and weekly training load.</p> <p>Contact and non-contact injuries were not differentiated.</p> <p>Small injury counts and the majority of the injuries did not result in any time-loss.</p> <p>History of previous injuries was not accounted for.</p> <p>The analysis does not account for the individual differences in training load which is not an appropriate method to evaluate the relationship between training load and risk of injuries.</p> <p>Non-linear effects of training load were not evaluated in this study.</p> |
| 15. Malone et al. (2017) | 48 professional soccer players (1 complete season) (Physical capacity) | Time-loss for contact and non-contact injuries, pre-season and in-season injuries analysed separately [75] Weekly (Nil and 1 week) | Cumulative 1-4 week load, week-to-week change in load, and ACWR for sRPE (4 levels based on arbitrary thresholds, 5 levels for week-to-week change) | <p>Pre-season:</p> <p>Higher risk of injury associated with moderate-low, moderate high, and high cumulative 1-4 week load and week-to-week change in load compared to the low level (odds ratios between 1.44 and 5.44).</p> <p>Lower risk of injury associated with moderate-high ACWR (>1 to <1.25) compared to low ACWR (<0.85) (odds ratio 0.68, 95%CI 0.08-1.66).*</p> <p>Higher risk of injury associated with high ACWR (>1.5) compared to low ACWR (<0.85) (odds ratio 2.33, 95%CI 1.69-4.75).</p> <p>In-season:</p> <p>Higher risk of injury associated with high cumulative 1-week and 4-week load, moderate-low 2-4 week load, and high week-to-week change in load compared to the low level (odds ratios between 2.11 and 3.11).</p> <p>Higher risk of injury associated with high ACWR (>1.5) compared to low ACWR (<0.85) (odds ratio 3.03, 95%CI 1.69-3.75).</p> |

16. Murray et al. (2017)

59 elite Australian football players (2 complete seasons)
-

Time-loss for non-contact injuries, pre-season and in-season injuries analysed separately [40]
Weekly
(Nil and 1 week)

Cumulative 1-week (acute) and 4-week (chronic) load and ACWR for 6 load constructs (total distance, player load, low, moderate, high, and very high speed distance)
(5 levels based on arbitrary thresholds)

*The authors' interpretation of the odds ratios is not consistent with the provided confidence intervals which are indicative of an unclear effect.

Contact and non-contact injuries were not differentiated.

History of previous injuries was not accounted for.

Training load was analysed against injuries in the current or subsequent week. Low training load could be the result of injury rather than a contributing factor to injuries. Such analysis is better suited to studies with a daily design.

Pre-season:

Lower risk of injury associated with very high acute total distance load compared to the moderate level during the subsequent week (relative risk 0.27, 95%CI 0.17-0.41).

Higher risk of injury associated with very high ACWR (>2) for total distance, low speed distance, and player load compared to the moderate level (1-1.49) during the subsequent week (relative risks between 4.87 and 12.46).

Higher risk of injury associated with very high ACWR (>2) for high speed distance compared to the low level (0.50-0.99) during the subsequent week (relative risk 6.46, 95%CI 4.63-9.02).

In-season:

Lower risk of injury associated with very high chronic total distance load compared to the very low level in the current week (relative risk 0.15, 95%CI 0.08-0.29).

Higher risk of injury associated with very high acute player load (unclear comparison group) during the subsequent week (relative risk 2.02, 95%CI 1.47-2.76).

Lower risk of injury associated with very high chronic total distance load compared to the very low level during the subsequent week (relative risk 0.20, 95%CI 0.01-3.02).*

Lower risk of injury associated with very high chronic low speed distance load compared to the very low level during the subsequent week (relative risk 0.33, 95%CI 0.01-18.70).*

17. Murray et al. (2017)

59 elite Australian football players (2 complete seasons)

-

Time-loss for non-contact injuries, pre-season and in-season injuries analysed separately [40]

Daily (1 day)

Rolling average ACWR and exponentially weighted moving average (EWMA) ACWR for 6 load constructs (total distance, player load, low, moderate, high, and very high speed distance) (5 levels based on arbitrary thresholds)

Pre-season:

Higher risk of injury associated with very high rolling average ACWR (>2) for total distance compared to the moderate level (1-1.49) (relative risk 8.41, 95%CI 1.09-64.93).

Higher risk of injury associated with very high EWMA ACWR (>2) for total distance, moderate speed distance, and player load compared to the moderate level (1-1.49) (relative risks between 6.03 and 9.53).

In-season:

Higher risk of injury associated with very high rolling average ACWR (>2) for total distance, high speed distance, and player load compared to the moderate level (1-1.49) (relative risks between 4.66 and 6.52).

Higher risk of injury associated with very high EWMA ACWR (>2) for total distance, moderate speed distance, and player

Higher risk of injury associated with very high ACWR (>2) for several constructs compared to multiple levels in the current and subsequent weeks (relative risks between 4.87 and 12.46).

A large spike in acute workload, resulting in a very high (>2.0) ACWR, was associated with an increase in injury risk in the current and subsequent week during the in-season period.

*The authors' interpretation of the relative risks is not consistent with the provided confidence intervals which are indicative of an unclear effect.

288 combinations of load, season phase, latent period, and comparison groups. Inflated risk of type I error.

Small injury counts considering separate analysis of pre-season (18) and in-season injuries (22).

Too many load levels considering the small injury count at each season phase.

History of previous injuries was not accounted for.

In the analysis of injuries in the current week, low training load could be the result of injury rather than a contributing factor to injuries. Such analysis is better suited to studies with a daily design.

| | | | | |
|--------------------------|--|---|---|--|
| 18. Murray et al. (2017) | 46 elite Australian football players (1 complete season) - | Match time-loss for contact and non-contact injuries [50] Proportion of pre-season training sessions completed was analysed against the in-season injury rates | Proportion of pre-season training sessions completed (3 quantiles) | <p>load compared to the moderate level (1-1.49) (relative risks between 13.43 and 21.28).</p> <p>The EWMA model explained substantially more variance in the injury risk compared to the rolling average model. EWMA ACWR is a more sensitive measure for detecting increased risk of injury compared to the rolling average ACWR.</p> <p>Small injury counts considering separate analysis of pre-season (18) and in-season injuries (22).</p> <p>History of previous injuries was not accounted for.</p> |
| 19. Owen et al. (2015) | 23 elite soccer players (2 complete seasons) (Body composition) | Time-loss for contact and non-contact injuries [119] 4-weekly and correlations between 4-weekly injury rates and 4-weekly training load over the study period (Nil) | Cumulative 4-week load for the time spent in the 85-90% of maximum heart rate (T-HI) and >90% of maximum heart rate (T-VHI). (2 quantiles) | <p>Athletes who completed <50% of pre-season training sessions were at a higher risk of injury during the competition period compared to athletes who completed >85% of the sessions (rate ratio 1.9, p-value 0.17, recalculated 95% confidence intervals 0.76-4.75).*</p> <p>*The provided p-value and the recalculated confidence intervals are indicative of an unclear effect.</p> <p>A likely reason for completing smaller proportions of the planned training sessions during pre-season is pre-season injuries. History of previous injuries (especially recent injuries) is an independent injury risk factor and the confounding effects of this variable was not accounted for in this study.</p> <p>Contact and non-contact injuries were not differentiated.</p> <p>Large correlations existed between total injury incidence and training intensity (T-HI: r=0.570, T-VHI: r=0.568).</p> <p>Correlations between match injury incidence and training intensity were not substantial.</p> <p>Higher risk of match injury was associated with high compared to low T-HI (odds ratio 1.87, 95%CI 1.12-3.12).</p> <p>Training load was solely from training sessions and did not contain the load from competitive matches.</p> <p>Training load was split into only 2 levels to evaluate the risk of injury which may obscure the potentially important effects at the higher and lower ends.</p> |

| | | | | |
|----------------------------|---|---|--|---|
| 20. Piggott et al. (2009) | 16 elite Australian football players (1 pre-season) - | Time-loss for contact and non-contact injuries [5] Weekly (1 week) | Week-to-week change in monotony, strain, and cumulative load for 4 load constructs (sRPE, total distance, high speed distance, and time spent in >80% of maximum heart rate) (One way repeated measures ANOVA was used) | Only 4-week blocks were used to evaluate the effects of training load which overlooks training load variations and effects over shorter time periods. History of previous injuries was not accounted for. Contact and non-contact injuries were not differentiated. 2 of the 5 injuries were associated with a preceding spike in training load.* *The sample size and injury counts were too small to draw meaningful conclusions from this study. Only 5 players wore the GPS units and the average values were used for the whole squad. |
| 21. Rogalski et al. (2013) | 46 elite Australian football players (1 complete season) (Professional experience) | Time-loss for contact and non-contact injuries, pre-season and in-season injuries analysed separately [238] Daily (Unspecified) | Cumulative 1-4 week load and week-to-week change in load for sRPE (4 levels based on arbitrary thresholds) | No substantial relationships between training load and risk of injury during pre-season. Higher risk of injury associated with moderate low (odds ratio 1.95, 95% CI 0.98-3.85), moderate high (2.44, 1.28-4.66), and high (3.38, 1.69-6.75) 1-week load compared to the low training load level during the in-season. Higher risk of injury associated with moderate high (4.03, 0.98-16.53), and high (4.74, 1.14-19.76) 2-week load compared to the low training load level during the in-season. Higher risk of injury associated with high week-to-week changes in load (2.58, 1.43-4.66) compared to the low week-to-week change level during the in-season. Contact and non-contact injuries were not differentiated. Strict interpretation of time-loss (238 injuries over one season) and did not account for history of previous injuries. |

| | | | | |
|--------------------------|---|--|--|---|
| 22. Ruddy et al. (2017) | 220 elite Australian football players (1 complete season) (Age, history of a previous hamstring and ACL injury) | MRI confirmed hamstring strain injuries [30] Weekly (1 week) | Cumulative 1-4 week load, absolute and relative week-to-week change in load, ACWR, and relative very high speed distance for 2 load constructs (distance >10 km.h ⁻¹ and distance >24 km.h ⁻¹) (2 levels based on receiver operator characteristic curve-derived cut-points) | Higher risk of injury associated with high 1-week load and absolute and relative week-to-week change in load compared to the low training load level for the distance >10 km.h ⁻¹ (relative risks between 2.2 and 2.6). Higher risk of injury associated with high 1-4 week load and absolute and relative week-to-week change in load compared to the low training load level for the distance >24 km.h ⁻¹ (relative risks between 2.1 and 3.9). Higher risk of injury associated with high (>2.5%) distance covered above 24 km.h ⁻¹ as a percentage of distance covered above 10 km.h ⁻¹ compared to the low (<2.5%) training load level (relative risk 6.3, 95%CI 1.5-26.7). Despite the substantial associations between the derived training load measures and the risk of hamstring strain injury, the derived measures could not predict injuries at the individual level with sufficient accuracy. Training load measures were split into only 2 levels to evaluate the risk of injuries which may obscure the potentially important effects at the higher and lower ends. History of hamstring injuries in the 12 months prior to the study and history of a previous ACL injury were evaluated in this study but only in a univariate analysis. The effects of previous hamstring injuries and other injuries in the current season were not adjusted for in the analysis of training load. |
| 23. Stares et al. (2017) | 70 elite Australian football players (4 in-seasons) (Age, professional experience) | Match time-loss for non-contact injuries [133] Weekly (7, 14, 21, and 28 days) | ACWR for various combinations of acute (1 and 2 weekly) load and chronic (3-8 weekly) load interacted with very low and low chronic load for 3 load constructs (on-legs sRPE, total distance, and sprint distance) (8 levels for ACWR based on arbitrary thresholds and 4 quantiles for chronic load) | Higher risk of injury associated with 13 different combinations of ACWR interacted with low and very low chronic load compared to the reference group (ACWR 0.9-1.2 and high chronic load) for a 7 day latent period (rate ratios between 2.25 and 8.19). All the high risk combinations had an ACWR of <0.6 or >1.5. Altering the acute and chronic periods in calculation of ACWR did not improve the model performance in detecting high injury risk conditions beyond the commonly used 1-week to 4-week ACWR. The increased risk of injury persists for up to 28 days after the occurrence of a high risk combination. |

| | | | | |
|-----------------------------------|--|--|---|--|
| 24. Thornton et al. (2017) | 25 professional rugby league players (3 complete seasons) (Playing position) | Time-loss for non-contact injuries [156] Daily (Unspecified) | Cumulative 7, 14, 21, and 28 day load, and ACWR for 4 load constructs (sRPE, total distance, high speed running distance, and high metabolic power distance) (Generalized estimating equations were used to identify the training load variables with the highest associations with injury risk) | Only 13 of the 279 load combinations had a substantial effect on the risk of injury for the 7 day latent period, which is likely the result of having too many (8) ACWR load levels. The issue is further complicated by having the ACWR levels interacted with a further 4 chronic load levels. This approach results in wide confidence intervals and a high chance of observing unclear effects for each of the combinations due to having small number of observations in each level (inflated risk of type II error). The magnitude of the observed clear effects will also be biased high. History of previous injuries was not accounted for. Only field training sessions contributed to the calculated training loads. Different measures had the highest associations with injury risk for different positional groups. The importance of each derived training load measure on injury incidence varied between individual players. The effects of derived measures on injury risk were not reported in this study. |
| 25. Veugelers et al. (2016) | 45 elite Australian football players (1 pre-seasons) - | Time-loss for non-contact injuries [13] Weekly (1 week) | Cumulative 1 and 2 week load for on-field and overall RPE and sRPE (2 quantiles) | Lower risk of injury associated with high 1-week sRPE, 1-week RPE, and 2-week RPE compared to the low level (odds ratios between 0.199 and 0.225). Training loads were split into only 2 levels to evaluate the risk of injury which may obscure the potentially important effects at the higher and lower ends. Small injury counts. History of previous injuries was not accounted for. |

| | | | | |
|-------------------------|---|---|--|--|
| 26. Windt et al. (2016) | 30 elite rugby league players (1 in-season) (Pre-season participation, age, position) | Match time-loss for contact and non-contact injuries [40] Weekly (Nil and 1 week) | Cumulative 1-week (acute) and 4-week (chronic) load and ACWR for 3 load constructs (total distance, high speed distance, and high speed distance as a percentage of total distance) (Linear associations – effect of 1 SD increase in training load) | <p>Lower risk of injury associated with a 1 SD increase in the acute total distance in the current week (odds ratio 0.64, 95% CI 0.46-0.90).</p> <p>Higher risk of injury associated with a 1 SD increase in the acute high speed distance as a percentage of total distance in the current week (odds ratio 1.34, 95% CI 1.03-1.73).</p> <p>Higher risk of injury associated with a 1 SD increase in high speed distance as a percentage of total distance in the subsequent week (odds ratio 1.07, 95% CI 1.06-1.08).</p> <p>After adjusting for training load of the current week, completing 10 additional pre-season sessions was associated with a 17% reduction in the odds of injury in the subsequent week during the in-season (OR=0.83, 95% CI=0.70 to 0.99).*</p> <p>* History of previous injuries was not accounted for. Completion of less sessions during pre-season could be the result of pre-season injuries. Players who were injury prone during pre-season will likely remain injury-prone during in-season.</p> <p>Non-linear effects of training load were not evaluated in this study.</p> <p>Contact and non-contact injuries were not differentiated.</p> |
|-------------------------|---|---|--|--|

Note: sRPE, session rating of perceived exertion; ACWR, acute-to-chronic workload ratio; EWMA, exponentially weighted moving average. All ACWR measures are 1-week load divided by the 4-week rolling average weekly load unless otherwise specified.

Medical attention injuries as the name suggests, are injuries resulting in a player seeking medical evaluation/treatment irrespective of whether the injury leads to any training or match time-loss (Fuller et al., 2006; Gabbett & Jenkins, 2011). Time-loss is the most commonly used definition of injury and can be subdivided into match time-loss and training/match time-loss. Training/match time-loss injury is defined as any injury that causes a player to be unable to fully participate in training activity or be unavailable for selection in a competitive match (King et al., 2009).

In addition to the medical attention or time-loss requirement, 15 of the 26 studies summarised in Table 2.1 also included the injury mechanism in their definition and only included non-contact injuries in their analysis (see for example reference numbers 2, 9, and 16), or analysed the contact and non-contact injuries separately (see for example reference numbers 1 and 10). The rationale behind inclusion of injury mechanism in the definition of injury is that contact injuries are considered mostly unavoidable considering the main contributing factor to injury being the force applied through the contact (Gabbett, 2010). On the other hand, non-contact injuries are deemed to be largely preventable and mainly influenced by excessive training and inadequate recovery (Gabbett, 2010). No studies to date have specifically evaluated the impact of distinction between contact and non-contact injuries on the magnitude of associations between training load and injury. While substantial associations may exist between training load and contact injuries, it can be speculated that inclusion of contact injuries in the analysis may dilute the observed effects of training load, potentially increasing the sample size required to observe clear effects.

Study 3 of this thesis (Chapter 5) utilized the training/match time-loss definition to evaluate the effects of training load and other risk factors on occurrence of non-contact injuries. It should also be noted that evaluating the effects of training load (or any other injury risk factor) on a specific type of injury requires a very large sample size in order to observe sufficient injury incidences for a meaningful analysis. As a result, only two of the identified studies have attempted this approach by only focusing on hamstring injuries (Duhig et al., 2016; Ruddy et al., 2016).

Latent period and analysis block were other points of difference between the studies summarised in Table 2.1. Latent period is defined as the time gap between the calculated derived measures (exposure) and the injury onset (outcome) (Drew & Finch, 2016). Analysis block refers to the time period that represents one observation in the analysis of derived measures of training load against injuries (unpublished observations). The majority of studies summarised had weekly analysis blocks with a latent period of one week (see for example reference numbers 5, 6, 7, 22, and 25). In other words, those studies evaluated the effects of the derived training load measures at the end of a given week against injuries that occurred over the subsequent week. A limitation of the weekly design (weekly analysis block) is that it disregards training load of the week of injury, which contain the most recent training sessions. It may not be appropriate for studies with a weekly design to analyse derived training load of a given week against injuries in that same week, as artificially low training load could potentially be recorded in that week secondary to the injury. In this scenario, a low training load may be the result of an injury rather than a contributing factor

to injury (Drew & Finch, 2016). Studies with a daily design do not have this limitation and can use rolling daily derived measures without the need for extended latent periods. In one study with a daily design, inclusion of latent periods of two and five days did not improve the ability of the devised model in explaining variation in injury risk compared to when derived measures were analysed against injuries on the same day (no latent period) (Carey et al., 2017). Daily load analysis also has the advantage of accounting for the variation in the break between games which could be a potential confounder in studies with a weekly design (Stares et al., 2018). The need for accurate recording of injury date (rather than injury week) and higher complexity of data analysis appear to be the only disadvantages of the daily analysis design. Study 3 of this thesis (Chapter 5) adopted a daily design with no latent period which allows for evaluation of the effects of actual training load completed by players up to the moment of getting injured on the risk of injury.

Another important point of difference between the evaluated studies of Table 2.1 is the number of analysed load levels. The number of load levels is primarily determined by the amount of data and specifically the number of injuries available for analysis, as well as the strength of associations between the identified risk factors and the outcome of interest (injuries) (Hopkins, 2006c). Injuries are essentially distributed between the determined load levels. While having higher number of load levels may provide a more accurate picture of the non-linear effects of training load, it reduces the number of load observations and injuries in each level and hence the likelihood of observing clear effects (Hopkins, 2006c). The majority of the identified studies used three to six levels for the analysis of

derived measures of training load (see for example reference numbers 5, 12, 16, and 21). Some studies used only two load levels due to the limited number of injuries which does not allow for evaluating the non-linear effects of training load and obscures the effects particularly at the higher and lower ends (see for example reference numbers 7, 22, and 25). A number of other studies defined too many load levels considering the number of injuries and analysis design, which led to observing unclear effects for most of the derived measures (see for example reference numbers 12, 16, and 23). Transforming the continuous predictor (training load) into too many categorical levels carries a high risk of type II error where the existent effects of training load are not detected owing to the limited data availability in each level. In addition, the magnitude of ratios for the clear effects are biased high, partially due to the larger gap in the dose of the predictor (training load) between the higher levels and the reference group. Study 3 of this thesis (Chapter 5) employed four load levels to evaluate the effects of training load on the risk of injury.

It should also be noted that descriptive labelling of load levels is dependent on the number of levels used in each study, and is an important point to consider when interpreting the findings of studies. The descriptive labelling of load levels commonly used in the literature are as follows: 2 levels (low, high), 3 levels (low, moderate, high), 4 levels (low, moderate-low, moderate-high, high), 5 levels (very low, low, moderate, high, very high), 6 levels (very low, low, moderate-low, moderate-high, high, very high).

The majority of the identified studies have reported substantial associations between high cumulative and relative training load of various time periods and a

higher risk of injury (Table 2.2). Mechanical stressors applied to the musculoskeletal structures through training drive the biomechanical adaptations in these tissues (Vanrenterghem et al., 2017). In the case of high cumulative training load, accumulation of normally transient detrimental changes in the tissues lead to weakening of the musculoskeletal structures, which may eventually reach a critical point and result in a tissue failure (Vanrenterghem et al., 2017). In contrast to these findings, three studies have reported substantial associations between high cumulative load and a lower risk of injury (Colby, Dawson, Peeling, et al., 2017; Hulin, Gabbett, Caputi, et al., 2016; Veugelers et al., 2016). It has been argued that players with high cumulative load may have been training within a desired range that in fact protects them against injuries (Veugelers et al., 2016). While it is indeed possible for athletes to respond well to a well-designed and closely monitored training program that involves high training load, it should also be considered that the three studies that found protective effects for high training load had a weekly design which overlooks the training load of the current week in the analysis. The training load of players in the current week could have been modified to mitigate the risk of injury based on the identified high cumulative load, which could have affected the findings.

Table 2.2 Comparison of the findings of studies investigating the relationship between training load and risk of injury in elite/professional football code athletes. Studies are as numbered in table 2.1.

| | High daily | High 1-week | High 2-week | High 3-week | High 4-week | Low 1-week* | Low >1-week* | High week-to-week change | High ACWR | Low ACWR |
|------------------------|------------|-------------------------|---------------|--------------|---------------------|-------------|--------------|--------------------------|--------------------------|------------|
| Higher risk | 10 | 6, 7, 9, 13, 15, 21, 22 | 7, 15, 21, 22 | 3, 7, 15, 22 | 3, 6, 7, 15, 19, 22 | | 5 | 6, 15, 20, 21, 22 | 2, 5, 12, 15, 16, 17, 23 | 2, 5, 23 |
| Lower risk | | 12, 25 | 5, 25 | | 12 | 1, 6, 13 | | | | 13 |
| Trivial/unclear | | 1, 3, 5, 14 | 3, 5 | 5, 21 | 5, 13, 16, 21, 26 | 5 | 13 | 3 | 26 | 12, 15, 17 |
| Mixed findings | 11 | 8, 16, 26 | | | 8 | | | | | |

*Only studies where the low level was not used as the reference group.

Notes: ACWR, acute-to-chronic workload ratio.

An inherent limitation of training load-injury risk studies in elite athletes is the risk of data contamination as a result of staff taking risk modifying actions based on the available data (Hewett, 2017). This inherent limitation becomes more prominent in studies with a weekly analysis design which could have resulted in the observed inconsistencies in the findings of the evaluated studies. In addition, low cumulative load could be the result of other risk factors such as previous injuries or presence of early signs and symptoms of maladaptation to training rather than a causative factor moderated through reduced fitness. None of the training load-injury risk studies have accounted for the possible confounding variables that affect both training load and risk of injuries. It should also be noted that no studies to date have evaluated the effects of exponentially weighted moving average cumulative load on the risk of injury. Cumulative load measures calculated using exponentially weighted moving averages can reflect the decaying nature of training effects and may provide a more accurate estimate of the relationship between training load and risk of injury (Menaspa, 2017a). Study 3 of this thesis (Chapter 5) compared the conventional cumulative load and exponentially weighted cumulative load in regards to their effects on the risk of injury.

High acute-to-chronic workload ratios have consistently been reported to be associated with an increased risk of injury (Table 2.2). Banister's fitness-fatigue model for athletic performance corresponds the acute load to the fatigue state and the chronic load to the fitness state (Banister et al., 1975). This model was later developed to derive an index of athletes' preparedness which is known as the acute-to-chronic workload ratio (Hulin et al., 2014). An acute-to-chronic

workload ratio >1 is indicative of recent load that is higher than the rolling average historical load (Gabbett, 2016). A high acute-to-chronic workload ratio is proposed to represent a situation where an athlete has a high level of acute fatigue without having developed the required level of fitness (Gabbett, 2016; Hulin et al., 2014) which can explain the observed associations between high acute-to-chronic workload ratios and higher risk of injury. A major limitation of acute-to-chronic workload ratio is the possible confounding effects of high acute load and recent injury. A high acute-to-chronic workload ratio could be the result of a very high acute load or a recent injury (resulting in a low chronic load), both of which have already been identified as independent injury risk factors. None of the studies evaluating the effects of acute-to-chronic workload ratio on the risk of injury have accounted for these possible confounding factors in their analysis in order to identify the degree to which the effects of acute-to-chronic workload ratio are explained by these variables. Another limitation of acute-to-chronic workload ratio is that the provided models do not allow for a progressive increase in capacity with loading. Instead, the only way to increase preparedness in the model is to reduce load.

Low acute-to-chronic workload ratio is associated with an increased risk of injury (Carey et al., 2017; Colby, Dawson, Peeling, et al., 2017; Stares et al., 2018). It has been argued that players with a low acute-to-chronic workload ratio are more likely to experience a spike in training load in the following week, which could explain the increased risk of injury (Colby, Dawson, Peeling, et al., 2017; Stares et al., 2018). Spikes or high week-to-week changes in training load are associated with a higher risk of injury (Cross et al., 2016; Malone et al., 2017; Piggott et al.,

2009; Rogalski et al., 2013; Ruddy et al., 2016). It should be considered that similar to high acute-to-chronic workload ratio, a high week-to-week change in training load may also be the result of a recent injury. Players who return back to full training or competition from an injury tend to experience high week-to-week changes in training load, and the observed effects of this variable may partly be explained by the history of a recent injury (Rogalski et al., 2013).

The thresholds for high and low acute-to-chronic workload ratios vary between studies and generally range between >1.2 and >2 for the highest level and <0.5 and <0.8 for the lowest level. Current recommendations have described acute-to-chronic workload ratios of between 0.8-1.3 as the “sweet spot” range where the injury risk is at its lowest, and the acute-to-chronic workload ratios of >1.5 as the “danger zone” where the injury risk increases exponentially with increases in the acute-to-chronic workload ratio (Blanch & Gabbett, 2016; Bourdon et al., 2017; Gabbett, 2016).

To summarize, there is strong evidence in support of training load monitoring for injury prevention purposes. Several methodological considerations should be taken into account in future studies to further refine our understanding and applicability of training load monitoring in injury prevention. These considerations include appropriate choice of injury definition, analysis block, and number of load levels, as well as accounting for the effects of previous injuries and using non-linear methods of deriving and analysing training load measures.

2.3 Tendon structure, response to changes in load, and the role of ultrasound imaging

2.3.1 Tendon structure

A tendon is a connective tissue primarily made of collagen and elastin embedded in a matrix of proteoglycan and water (Józsa, Bálint, Réffy, & Demel, 1979; Kannus, 2000). Collagen and elastin comprise 65-80% and 1-2% of the dry mass of tendon, respectively, and are produced by the tenoblasts and tenocytes that lie between the collagen fibers (Józsa, Lehto, Kvist, Bálint, & Reffy, 1989; O'Brien, 1997). These components are organized in a hierarchical arrangement to form a tendon (Figure 2.2) (O'Brien, 1997).

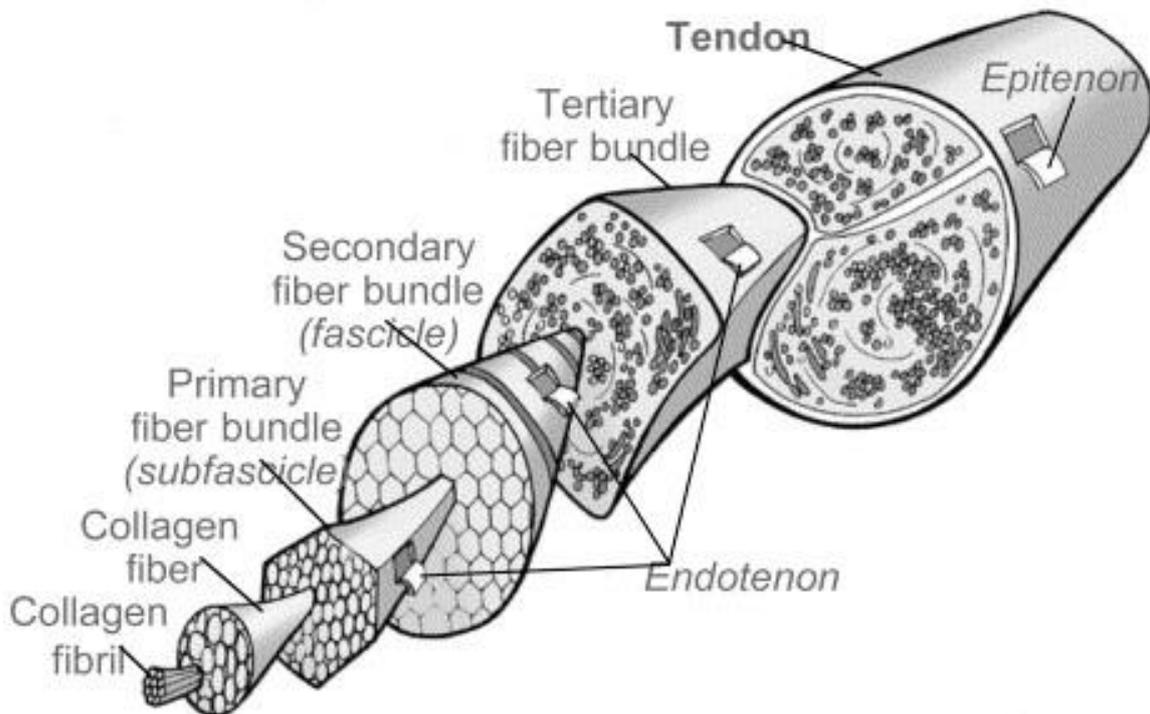


Figure 2.2. Structural organization of tendon. Reproduced from Ashe et al. (2004).

Microfibril or tropocollagen is the structural unit of collagen, and a group of microfibrils bind together to form collagen fibrils. A number of parallel fibrils set in the extracellular matrix form a fiber, and a group of fibers enclosed by a sheath of connective tissue called endotenon form a fascicle (O'Brien, 1997). In addition to binding the fibers together, endotenon enables the fiber groups to glide on each other, and it also carries the blood vessels, lymphatics, and nerves deep in the tendon (Kannus, 2000). Fascicles are surrounded by another layer of connective tissue called epitenon and make up the body of tendon (O'Brien, 1997).

The main function of tendons is transmission of tensile forces generated by the muscles to the bones. As a result, fibrillar alignment is a key factor in tendon function (Ottani, Raspanti, & Ruggeri, 2001; Woo, 1986). Orientation of fibers in the direction of tensile stresses is the most efficient way of maximizing tendon strength without increasing the tendon size and metabolic cost (Ottani et al., 2001). In addition to the longitudinal tensile forces, tendons need to withstand some transversal and torsional forces during different stages of movement, and also cope with direct forces and contusions (Kannus, 2000). Therefore, while the majority of tendon fibers run longitudinally along the length of the tendon, some fibers cross each other and travel in transverse direction (Józsa, Réffy, & Bálint, 1984). The ratio of longitudinal to transverse (or horizontal) fibers varies between 10:1 and 26:1 (Jozsa, Kannus, Balint, & Reffy, 1991). The complex structure of tendons allows them to develop a capacity against forces of various directions, and prevents premature rupture of the fibers (Kannus, 2000).

The structural properties of the tendon refer to mechanical, material, and morphological features that directly affect the tendon function by determining its load transferring capacity and efficiency (Couppé et al., 2012; Kubo, Kanehisa, Kawakami, & Fukunaga, 2000; Roberts, 2002). Tendon stiffness ($\Delta\text{force}/\Delta\text{deformation}$), elastic (Young's) modulus ($\Delta\text{stress}/\Delta\text{strain}$), and cross-sectional area are the three widely studied measures that represent the mechanical, material, and (macro)morphological properties of tendon, respectively (Wiesinger, Kösters, Müller, & Seynnes, 2015). Tendon stiffness measures the change in tendon length relative to the applied force. The original tendon length and cross-sectional area affect the tendon stiffness in a way that shorter length and higher cross-sectional area result in a stiffer tendon (Heinemeier & Kjaer, 2011). A higher tendon stiffness generally translates into higher efficiency in transferring forces from muscles to bones (Witvrouw, Mahieu, Roosen, & McNair, 2007). Elastic modulus measures the tendon stress (tendon force divided by cross-sectional area) in relation to the tendon strain (change in length divided by normal length). In other words, modulus measures the actual material properties of the tendon regardless of the cross-sectional area, which allows for comparing tendons of different sizes (Heinemeier & Kjaer, 2011). A higher elastic modulus is indicative of a higher energy storage/release capacity of the tendon during stretch-shortening cycles which is generally considered as an energy-saving characteristic (Witvrouw et al., 2007).

The discussed structure and structural properties are dynamic features of tendon, and a number of adaptations in tendon structure occur in response to changes in forces applied to the tendon.

2.3.2 Tendon response to changes in load

Periods of training and injury are characterized by considerable increase or decrease in magnitude and frequency of force that tendons normally transfer, referred to as episodes of loading or unloading (Dideriksen, 2014). The episodes of loading and unloading lead to changes in tendon structure through various mechanisms.

Collagen proteins are in a constant process of breakdown and synthesis, which is known as collagen turnover (Birch, 2007). Collagen protein synthesis decreases following unloading periods as short as 10 days, which shifts the balance of collagen turnover in tendons towards an overall breakdown (De Boer et al., 2007). The cross links between collagen fibers also decrease as a result of episodes of unloading, and combined with the overall collagen breakdowns eventually alter the material and mechanical properties of a tendon (Boesen et al., 2013; Couppé et al., 2012; Kubo et al., 2004). A 50% increase in the Achilles tendon stiffness gained by three months of training was lost after only one month of detraining, concurrent with changes in the structure of collagen fibers (Kubo, Ikebukuro, Maki, Yata, & Tsunoda, 2012). Large reductions in patellar tendon stiffness and elastic modulus occurred following two weeks of unilateral lower limb immobilization, which coincided with decreased expression of an enzyme (lysyl oxidase) responsible for formation of collagen cross links (Boesen et al., 2013; Couppé et al., 2012). The reductions in stiffness and elastic modulus were not accompanied by changes in tendon cross-sectional area following a two-week lower limb immobilization (Boesen et al., 2013), indicating that solely changes in internal tendon structure are responsible for changes in tendon

mechanical and material properties as a short-term response to an unloading episode.

As discussed above, detrimental changes in tendon mechanical and material properties occur following episodes of unloading, which limit the capacity of tendon in its key function of transferring force. This compromised tendon functional capacity can partially explain the increased risk of injury in athletes following their return from an injury episode. The effects of previous injuries on the risk of subsequent/recurrent injuries will be further discussed in section 2.5.

Episodes of controlled loading reverse the unloading-induced changes in tendon structure and the mechanical and material properties (Boesen et al., 2013; Kubo et al., 2012; Wiesinger et al., 2015). Collagen synthesis in tendons increases following both acute exercise (1 hour) (Miller et al., 2007) and long term training (20 hours per week over 11 weeks) (Langberg, Rosendal, & Kjær, 2001). While both collagen synthesis and degradation increase at the early stages of training, the anabolic processes prevail later on and result in net formation of collagen (Langberg et al., 2001). Gene expression of the enzyme that facilitates collagen cross link formation (lysyl oxidase) also increases after episodes of loading (Boesen et al., 2013). The net increase in collagen synthesis and cross-link formation following training is proposed to be the main contributor to adaptive changes in tendon material, mechanical, and morphological properties (Wiesinger et al., 2015).

Increased synthesis of extra cellular matrix proteins as a result of the mechanotransductive response of fibroblasts also improves the tendon strength

and its force transmission capacity (Kjaer, 2004; Wiesinger et al., 2015). Tendon stiffness and elastic modulus increase by 20-80% following 6-12 weeks of training (Kubo et al., 2009; Kubo, Kanehisa, & Fukunaga, 2002; Malliaras et al., 2013). Similar training periods result in no changes or only a 3-6% increase in tendon cross-sectional area (Kongsgaard et al., 2007; Seynnes et al., 2009; Wiesinger et al., 2015). On the other hand, tendon cross-sectional area of long term athletes is larger than non-athletes by at least 20%, which indicates that the process of change in tendon cross-sectional area is relatively slow compared to the adaptations in tendon stiffness and elastic modulus (Kongsgaard, Aagaard, Kjaer, & Magnusson, 2005; Magnusson et al., 2003; Rosager et al., 2002; Wiesinger et al., 2015). In addition, changes in tendon cross-sectional area are limited to specific regions of the tendon (Kongsgaard et al., 2007; Wiesinger et al., 2015). In one study, 12 weeks of resistance training resulted in cross-sectional area of patellar tendons to increase by 6% and 4% in the proximal and distal portions, respectively, while no changes occurred at the mid tendon level (Kongsgaard et al., 2007). While the exact mechanisms behind the inhomogeneous hypertrophy of patellar tendon are unknown, compressive loads applied to the tendon at the two ends by the patella and tibia could be the key factors. Synthesis of extracellular matrix proteins is stimulated by the compressive loads allowing the tendon to adapt to the compressive mechanical stimuli (Malaviya et al., 2000; Robbins, Evanko, & Vogel, 1997).

Episodes of controlled loading also reduce the distance between tendon fibrils and increase the tendon fibrillar density, as well as the extra cellular matrix proteins (Kongsgaard et al., 2010; Wiesinger et al., 2015). The increase in tendon

fibrillar density and extracellular matrix proteins explains the changes in tendon stiffness and elastic modulus without the need for concomitant changes in tendon cross-sectional area following episodes of loading and unloading (Couppé et al., 2012; Wiesinger et al., 2015).

It can be concluded that changes in material and mechanical properties are the relatively short term responses of tendon to changes in load, while changes in tendon macromorphology (cross-sectional area) are the long term adaptations that may require years of training. Based on the discussed timelines and mechanisms, the 18 week period of pre-season training chosen for the study 1 of this thesis (Chapter 3) is long enough for possible adaptations in the measure of interest (internal tendon structure/fibrillar alignment) to occur.

2.3.3 Asymmetries between the dominant and non-dominant sides

Asymmetries may exist between the structural properties of the tendons of the dominant and non-dominant sides. Achilles and patellar tendons are among the most commonly injured tendons (Maganaris, Narici, Almekinders, & Maffulli, 2004) particularly in football athletes (Orchard et al., 2013b; Waldén, Hägglund, & Ekstrand, 2005). Table 2.3 summarizes the studies that have investigated the differences between the Achilles and patellar tendons of the dominant and non-dominant sides in material, mechanical, and morphological properties (Bohm, Mersmann, Marzilger, Schroll, & Arampatzis, 2015; Couppe et al., 2008; Pang & Ying, 2006; Pfirrmann, Jost, Pirkl, Aitzetmüller, & Lajtai, 2008; Ying et al., 2003; Zhang, Ng, & Fu, 2015). A comparison of the findings of these studies indicate that small differences of generally less than 10% exist between the structural properties of the Achilles and patellar tendons of the two sides in physically active

individuals (Bohm et al., 2015; Pang & Ying, 2006; Ying et al., 2003). Asymmetries in structural properties of Achilles and patellar tendons are also present in athletes involved in sports that require some asymmetrical loading of the Achilles or patellar tendons (Zhang et al., 2015). The level of asymmetry increases as the sport-induced side to side differences in tendon loading increase. Side to side asymmetries of up to 36% in stiffness exist in the patellar tendons of elite fencers and badminton players, who need to frequently lunge on their lead leg (dominant side) (Couppe et al., 2008). It can be concluded that the symmetry of the structural properties of the Achilles and patellar tendons of the dominant and non-dominant sides cannot be assumed. Some sport specific activities require asymmetrical loading of the tendons of the dominant and non-dominant sides that will eventually lead to slightly different adaptations in the tendons of the two sides, in accordance with the adaptive mechanisms discussed in the previous section (see section 2.3.2). Tendon side to side asymmetries have not previously been investigated in athletes in any of the football codes. The differences between the internal structure of the dominant and non-dominant Achilles and patellar tendons of elite Australian footballers have been investigated as part of study 1 of this thesis (Chapter 3).

Table 2.3. Summary of studies investigating the differences in structural properties between the dominant and non-dominant Achilles and patellar tendons.

| Author (year) | Participants | Tendon (measure of interest) | Findings/Comments |
|---------------------------------|--|---|---|
| Ying et al. (2003) | 40 healthy individuals - frequent and infrequent exercise groups | Achilles (CSA) | <p>The CSA of the dominant Achilles tendon in the frequent exercise group was approximately 10%* larger than the infrequent exercise group.</p> <p>The CSA of the dominant Achilles tendon was approximately 6%* larger than the non-dominant side in the frequent exercise group, which did not reach statistical significance (exact p-values and SD not provided).</p> <p>*Small standardized difference based on the provided figure.</p> |
| Zhang et al. (2015) | 40 participants (10 sedentary individuals, 15 basketball players, 15 volleyball players) | Patellar (shear elastic modulus, CSA) | <p>The dominant patellar tendon had an approximately 10% higher shear elastic modulus compared to the non-dominant side in basketball players (small standardized difference) but no differences existed between the two sides in volleyball players and sedentary individuals.</p> <p>No differences existed between the two sides in tendon CSA in either groups.</p> |
| Pfirschmann et al. (2008) | 202 professional beach volleyball players | Patellar (diameter) | <p>No differences between the dominant and non-dominant sides in patellar tendon diameter.</p> <p>Tendon CSA was not measured. Tendon CSA (and not the diameter) directly affects the mechanical properties of tendon.</p> |

| | | | |
|--------------------------|---------------------------------------|---|--|
| Pang & Ying (2006) | 40 healthy individuals | Achilles (CSA, diameter, length) | The CSA of the dominant Achilles tendon was approximately 8.5% larger than the non-dominant side (small standardized difference). No differences between the two sides in length and diameter. |
| Bohm et al. (2015) | 36 physically active individuals | Achilles (elastic modulus, stiffness, CSA) | The elastic modulus of the dominant Achilles tendons was approximately 13% larger than the non-dominant side No differences between the two sides in CSA (trivial standardized difference). The stiffness of the dominant side was approximately 6% larger than the non-dominant side but the difference was not statistically significant. Standardized difference was marginally trivial (0.17). Exact p-values are not provided and confidence limits cannot be calculated. A larger sample size may provide clear results. |
| Coupepe et al. (2008) | 7 elite fencers and badminton players | Patellar (CSA, stiffness, elastic modulus) | Patellar tendon CSA of the lead leg (dominant side) was 20% and 28% larger at the proximal and distal ends compared to the non-lead leg (non-dominant side). The patellar tendon stiffness of the lead leg was 36% higher compared to the non-lead leg. There were no differences between the two sides in the elastic modulus. The large magnitude of asymmetry is possibly due to the substantial sport-induced side to side quadriceps strength difference (22%). |

CSA, cross-sectional area; SD, standard deviation.

2.3.4 The tendon pathology continuum

Tendinopathy refers to a clinical condition that features tendon pain and dysfunction irrespective of the underlying pathology (Maffulli, 1998). Detrimental changes in tendon structure reduce the tendon capacity to sustain repeated tensile loads (Cook & Purdam, 2009), and tendinopathy symptoms aggravate with increased loading (Cook, Khan, & Purdam, 2002; Rio et al., 2014). A theoretical model describes the continuum of load-induced tendon pathology in three stages (Cook & Purdam, 2009).

The first stage of load-induced tendon pathology is referred to as the reactive tendinopathy stage during which acute tensile or compressive overload elicits a non-inflammatory proliferative response in the tendon cells and matrix (Cook & Purdam, 2009; Scott et al., 2007). As a result of the proliferative response, short term tendon thickening occurs, which is different from the normal adaptive response of change in tendon elastic modulus and subsequently stiffness as discussed earlier (section 2.3.2) (Cook & Purdam, 2009). This quick tendon thickening response is possible through upregulation in synthesis of some glycoproteins (hyaluronan) and larger proteoglycans associated with pathological tendons (aggrecan and versican) (Cook & Purdam, 2009; Samiric, Ilic, & Handley, 2004). The short term reactive response only needs minutes to a few days to occur, while the increase in small proteoglycans found in normal tendons requires approximately 20 days to occur (Cook & Purdam, 2009; Samiric et al., 2004). The ultrasound image of tendon at this stage shows an increase in tendon diameter and diffuse hypoechogenicity among normal collagen structures (Malliaras & Cook, 2006; Malliaras, Purdam, Maffulli, & Cook, 2010). The reactive response

of the tendon and the associated thickening can return to normal if the tendon overload is adequately reduced or enough time gap is allowed between the loading sessions (Cook & Purdam, 2009).

The continuation of the tendon overload and maladaptive responses pushes the tendon forward on the pathology continuum, and the tendon enters the dysrepair stage (Cook & Purdam, 2009). The tendon increases its number of cells (mainly chondrocytes and myofibroblasts), which leads to a substantial increase in protein synthesis and subsequently separation of the collagen fibers and disorganization of the matrix (Cook & Purdam, 2009). As a result of the separation of collagen fibers, small focal areas of hypoechogenicity appear on the ultrasound image (Cook & Purdam, 2009). The changes in tendon structure can still be reversed to some extent through load management and therapeutic exercises (Cook & Purdam, 2009; Öhberg, Lorentzon, & Alfredson, 2004).

The third stage of tendon pathology is characterized by progression of detrimental changes in the tenocytes and matrix, which results in areas of cell death and is referred to as degenerative tendinopathy (Kraushaar & Nirschl, 1999). Degenerated areas are filled with vessels, products of matrix breakdown and little collagen, and are scattered between areas of normal tendon and other stages of pathology (Cook & Purdam, 2009). This third stage of pathology has little potential for reversibility and pathological tendons attempt to maintain their load bearing capacity by increasing their cross-sectional area (Docking & Cook, 2015). Extensive hypoechoic regions are present in the ultrasound image of a tendon with this stage of pathology (Cook & Purdam, 2009). Large areas of degenerative tendinopathy compromise the tensile strength of tendons and predispose them

to rupture (Nehrer et al., 1997). In one study, nearly all non-traumatic tendon ruptures (97%) were preceded by degenerative changes in tendon structure while such changes existed in only 34% of the control tendons (Kannus & Jozsa, 1991). As described above, ultrasound imaging is a valuable tool that allows for evaluation of tendon structure and different stages of tendon pathology.

2.3.5 Ultrasound imaging and the risk of developing tendinopathy symptoms

Parallel organization of tendon fibers results in a single reflection of ultrasound waves when the ultrasound probe is perpendicular to the long tendon axis (Martinoli, Derchi, Pastorino, Bertolotto, & Silvestri, 1993). The parallel fiber arrangement may become compromised in pathological tendons, which leads to multiple reflections and shadowing evident as hypoechoic areas in the ultrasound image (Rasmussen, 2000). Abnormalities on the ultrasound image are not always accompanied by clinical symptoms of tendinopathy. Up to 59% of individuals with ultrasound-detected tendon abnormalities did not exhibit any tendon pain or dysfunction, which is indicative of some level of disconnect between tendon structure and clinical symptoms (Docking, Ooi, & Connell, 2015). While a disconnect between tendon structure and clinical symptoms limits the accuracy of ultrasound imaging as a stand-alone diagnostic tool, its prognostic value has been highlighted in the literature (Docking et al., 2015).

Tendons with ultrasound-detected abnormalities are at a higher risk of developing tendinopathy symptoms compared to ultrasonographically normal tendons. Table 2.4 summarizes the studies that have investigated the association between ultrasound-detected abnormalities in asymptomatic tendons and the risk of

developing tendinopathy symptoms in athletes of various sports (Cook, Khan, Kiss, Coleman, & Griffiths, 2001; Fredberg & Bolvig, 2002; Fredberg, Bolvig, & Andersen, 2008; Giombini et al., 2013; Malliaras & Cook, 2006; Malliaras, Cook, Ptasznik, & Thomas, 2006).

All but one study listed in Table 2.4 with a very small sample size (Cook et al., 2001) demonstrated an increased likelihood of developing symptoms in ultrasonographically abnormal Achilles or patellar tendons. Some of the evaluated studies suffered from small sample sizes (24-54 participants) and as a result, limited incidence of symptom development (0-5 cases) in both the exposed group (asymptomatic participants with ultrasound abnormality at initial assessment) and the unexposed group (asymptomatic participants without ultrasound abnormality at initial assessment). The small sample size and the rarity of symptomatic cases resulted in large uncertainties in the magnitude of findings (relative risk) (Malliaras & Cook, 2006), use of statistical procedures incapable of calculating relative risk (Fredberg & Bolvig, 2002; Giombini et al., 2013), or potentially important effects being unclear (Cook et al., 2001). Despite the differences between the evaluated studies in participants' activity type and level presented in Table 2.4, it can be estimated that on average 1 in 3-4 athletes with ultrasound-detected tendon abnormalities develop tendinopathy symptoms, and their risk is 2-3 times higher than the risk for athletes with normal ultrasound images (Table 2.4).

It is evident in the studies listed in Table 2.4 that there is inconsistency in the definition of ultrasound tendon abnormality, with a heavy reliance on subjective evaluation of ultrasound images. Traditional assessment of ultrasound images is

limited to classifying tendons as normal or abnormal, or subjectively grading the level of pathology based on a combination of pathological features (Docking et al., 2015). The objective evaluation of ultrasound images has been restricted to measuring the tendon dimensions (diameter or cross-sectional area) and quantification of hypoechoic regions as a percentage of tendon cross-sectional area (Docking et al., 2015). A comparison between histopathological evaluation of pathological tendons and subjective assessment of the ultrasound images has revealed that the regions surrounding the hypoechoic areas also contain some degrees of tendon pathology, which are shown as normoechoic on the ultrasound image (Movin et al., 1998). In addition, a number of technical factors associated with the traditional method of obtaining the ultrasound image (transducer tilt and angle, gain, depth) can negatively affect the reliability of the acquired images (Rosengarten et al., 2015; van Schie et al., 2010). Limitations of conventional ultrasound imaging do not allow for quantification of subtle changes in tendon structure, which is particularly important in evaluation of the response to training in healthy athletes. Ultrasound tissue characterization is a novel approach, which was developed to overcome these limitations.

Table 2.4. Summary of studies investigating the relationship between ultrasound-detected tendon abnormalities and the risk of developing tendinopathy symptoms.

| Author (year) | Participants (follow up period) | Tendon (Ultrasound abnormality definition) | Findings^a | Comments |
|------------------------------|---|---|--|--|
| Fredberg et al. (2008) | 209 professional soccer players (1 year) | Achilles (Spindle-shaped thickening of >1 mm relative to the normal distal part of the tendon) | Increased risk of developing symptoms (relative risk 2.6, 95% confidence interval 1.6- 4.9) Symptoms developed in 36% of players in the exposed group and 13% of players in the unexposed group | The relative risks were calculated for the combined control group and intervention group who received prophylactic eccentric training, which could have affected the findings. The risk was calculated for players rather than tendons. This approach accounts for the dependency of tendons of the two sides within athletes but has an increased risk of error when tendon abnormalities are unilateral. |
| | | Patellar (Thickening and a hypoechoic region >2 mm) | Unclear change in the risk of developing symptoms (relative risk 2.2, 95% confidence interval 0.9-5.7) Symptoms developed in 12% of players in the exposed group and 5% of players in the unexposed group | The relative risk of developing symptoms in Achilles tendons can be interpreted as a clear effect based on the smallest important relative risk of 0.9 and 1.1 for decrease and increase in injury risk, respectively (Hopkins, 2010). |

| | | | | |
|-------------------------|---|--|---|---|
| Malliaras & Cook (2006) | 101 volleyball players (1 season = 5 months) | Patellar (A focal hypoechoic region and/or diffuse thickening of the proximal tendon) | Increased risk of developing symptoms (relative risk 14.6, 95% confidence interval 1.9-111.4) Symptoms developed in 9 of 45 tendons (20%) in the exposed group and 1 of 73 tendons (1.4%) in the unexposed group | Only one tendon from the unexposed group (normal ultrasound) became symptomatic hence the large relative risk and wide confidence interval. Symptoms were only assessed at the beginning and the end of the season. This approach overlooks the tendons that become symptomatic for a limited period during the season. |
| Giombini et al. (2013) | 37 elite fencers (3 years) | Achilles (A focal hypoechoic region, focal or diffuse thickening, or diffused hypoechogenicity) | No difference in the likelihood of developing symptoms ($p=0.054$, Fisher's exact test) Symptoms developed in 1 of 4 tendons (25%) in the exposed group and 0 of 70 tendons in the unexposed group | Small sample size. None of the tendons from the unexposed group (normal ultrasound image) developed symptoms and as a result, relative risks could not be calculated. The long gap (3 years) between the two assessments ignores all the symptomatic episodes and structural changes during this period. Larger sample is required and the findings should be interpreted with caution. |
| | | Patellar (As above) | Increased likelihood of developing symptoms ($p<0.05$, Fisher's exact test) Symptoms developed in 2 of 8 tendons (25%) in the exposed group and 0 of 66 tendons in the unexposed group | |

| | | | | |
|--------------------------|--|--|--|---|
| | | Quadriceps (As above) | No difference in the likelihood of developing symptoms Symptoms developed in 0 of 3 tendons in the exposed group and 0 of 71 tendons in the unexposed group | |
| Malliaras et al. (2006) | 94 volleyball players (1 season = 5 months) | Patellar (A focal hypoechoic region and/or diffuse thickening of the proximal tendon) | Increased risk of developing symptoms (relative risk 2.6, recalculated based on the provided information) Symptoms developed in 11 of 45 tendons (24.4%) in the exposed group and 7 of 73 tendons (9.6%) in the unexposed group | Symptoms were only assessed at the beginning and the end of the season. The exclusion criteria (symptoms at the initial assessment) was applied to tendons rather than athletes. |
| Fredberg & Bolvig (2002) | 54 elite soccer players (1 year) | Achilles (Spindle-shaped thickening of >1 mm in relation to the normal distal part of the tendon) | Increased likelihood of developing symptoms ($p < 0.05$, Fisher's exact test) Symptoms developed in 5 of 11 tendons (45.4%) in the exposed group and 1 of 85 tendons (1.1%) in the unexposed group | Small sample size. The exclusion criteria (symptoms at the initial assessment) was applied to tendons rather than athletes, which could have resulted in overestimation of the likelihood of developing symptoms in the exposed group. Achilles tendon structure would likely be compromised on both sides in |

| | | | | |
|--------------------|---|--|--|---|
| | | Patellar (Hypoechoic regions >1 mm) | Increased likelihood of developing symptoms (p<0.05, Fisher's exact test) Symptoms developed in 3 of 18 tendons (16.6%) in the exposed group and 0 of 80 tendons in the unexposed group) | individuals with unilateral symptoms (Docking, Rosengarten, Daffy, & Cook, 2014). |
| Cook et al. (2001) | 24 football, basketball, and cricket players (mean 47 months, SD ±12 months) | Patellar (A hypoechoic region and/or fusiform swelling) | No substantial difference in the likelihood of developing symptoms (p=0.19, Fisher's exact test) Symptoms developed in 4 of 18 tendons (22.2%) in the exposed group and 2 of 28 tendons (7.1%) in the unexposed group | Participants filled out questionnaires regarding level of activity and symptoms at the beginning and the end of a long follow up period, which increases the risk of recall bias. Substantial differences between the exposed and unexposed groups in activity level and sport could have affected the results. The authors stated that there was a trend towards an association between ultrasound abnormalities and risk of developing symptoms that did not reach statistical significance. The likely reason behind the observed unclear effect is the small sample size. |

^aFindings are expressed as the risk of developing symptoms for athletes with ultrasound-detected tendon abnormalities relative to athletes without the tendon abnormalities.

Notes: SD, standard deviation

2.3.6 Ultrasound tissue characterization (UTC)

Ultrasound tissue characterization (UTC) combines an ultrasound transducer with an automatic transducer-tracking device and image-analysing algorithms in order to semi-quantify the internal tendon structure (micromorphology) (Rosengarten et al., 2015; van Schie et al., 2010). A conventional ultrasound probe is fitted within the tracking device, which is comprised of a transducer mount, an acoustic stand-off pad, and a transducer moving motor. This set up standardizes the transducer tilt and gain as well as the depth and focus setting, which are all common sources of error and reduced reliability in conventional ultrasonography (Rosengarten et al., 2015; van Schie et al., 2010). The transducer moves along the length of the tendon and captures hundreds of ultrasound images at 0.2 mm intervals. These images are then combined in an exclusively developed software, which renders a three-dimensional data block of the scanned tendon (Figure 2.3).

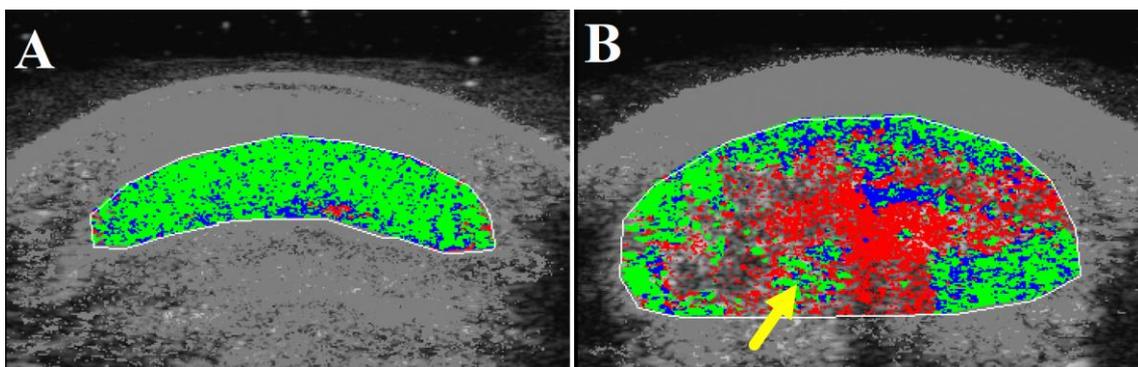


Figure 2.3. Ultrasound tissue characterization (UTC) images of patellar tendon. (A) Normal tendon structure (B) Degenerative tendinopathy indicated by areas of disorganized and fibrillar tissue (red) and amorphous matrix (black).

Each ultrasound image is a combination of structure-related echoes created at tendon bundles and interference arising from smaller units such as fibrils, cells,

and fluid (van Schie & Bakker, 2000; van Schie, Bakker, Jonker, & van Weeren, 2001; van Schie et al., 2010). While structure related echoes are stable over multiple contiguous transverse cross sections, the interference echoes are variable (van Schie et al., 2010).

Four distinct echo-types have been distinguished based on the three-dimensional stability of the ultrasound echoes. Echo-type I is highly stable and corresponds with intact, aligned, and continuous tendon bundles; echo-type II is medium stable and represents less continuous, less integer, and waving bundles; echo-type III is highly variable and relates to disorganized and fibrillar tissue; and echo-type IV is constantly low at echoes' intensity and highly variable, which characterizes amorphous matrix with loose fibrils, cells, or fluid (van Schie et al., 2010). These four echo-types have been validated against histopathological specimens from equine tendons by precise matching of UTC processed images to the corresponding section of the tendons (van Schie et al., 2001; van Schie, Bakker, Jonker, & Weeren, 2003; van Schie, Bakker, Jonker, & Weeren, 2000). The UTC software quantifies the internal tendon structure as percentages of these four echo-types with excellent inter-tester and intra-tester reliability (intraclass correlation coefficient >0.92) (van Schie et al., 2010).

A UTC window size refers to the section of tendon over which the stability of the echopattern is quantified (Docking, 2015). Window sizes of 25, 17, and 9 corresponding to distances of 4.8 mm, 3.4 mm, and 1.8 mm can be selected using the UTC software. A reduction in the window size generally results in a reduction in echo-type I (Docking, 2015). Consistent with several previous UTC studies (Docking & Cook, 2015; Docking, Rosengarten, & Cook, 2016; Docking et al.,

2014; Rosengarten et al., 2015), the window size of 25 was selected in the study 3 of the current thesis.

Training-induced changes in tendon material properties (elastic modulus), mechanical properties (stiffness), and macromorphology (cross-sectional area) have been widely investigated as discussed earlier (section 2.3.2). The introduction of UTC to human tendon research provided the opportunity to assess the subtle changes in tendon micromorphology (internal structure) in response to training. Two studies to date have assessed the changes in internal tendon structure in response to training (Docking et al., 2016; Rosengarten et al., 2015).

The structure of the left Achilles tendon of AFL players exhibited transient detrimental changes with a match stimulus. The proportion of echo-type I reduced two days post-match, coinciding with an increase in echo type II, with both returning to baseline by 4 days post-match (Rosengarten et al., 2015). Contrary to the findings of impaired tendon structure with an acute high load (Rosengarten et al., 2015), sustained periods of more consistent and controlled high load over an AFL pre-season training period improved the Achilles tendon structure, as indicated by a substantial increase in echo-type I and reductions in the three other echo-types (Docking et al., 2016). However, individual training load was not quantified and it is not clear to what extent the individual training load over the pre-season can affect the changes in tendon structure. Study 1 (Chapter 3) of this thesis investigates the effects of training load and leg dominance on the changes in the Achilles and patellar tendon structure of elite Australian footballers over the pre-season training period.

2.4 Musculoskeletal screening

2.4.1 Background

Screening in general medicine, is a strategy involving measurement of certain variables that assist with the detection of a disease in individuals who do not demonstrate any signs or symptoms of that disease (Bahr, 2016). The purpose of screening is early identification of pathological conditions, which will in turn allow for early intervention and hopefully a reduction in future morbidity and mortality (Bahr, 2016).

Musculoskeletal screening in sports refers to a series of tests that aim to identify athletes who are at a higher risk of injury by measuring and monitoring musculoskeletal-related injury risk factors (Maffey & Emery, 2006). In other words, musculoskeletal screening tests are designed to detect the presence of intrinsic injury risk factors before an injury occurs (Maffey & Emery, 2006). Targeted interventions such as treatments, injury prevention exercises, and training modifications will then be implemented to address the identified risk factors with the hope of reducing the injury risk of the predisposed athletes (Bahr, 2016; Robertson, Bartlett, & Gatin, 2017).

Musculoskeletal screening is primarily based on the previously identified associations between the risk of injury and specific musculoskeletal measures such as muscular strength and flexibility, which are classified as modifiable intrinsic risk factors (Bahr, 2016; Meeuwisse, 1994a). The injury profile of a sport determines the battery of tests included in the musculoskeletal screening. Each screening test focuses on a risk factor for a particular injury that is relatively

common in that sport (Batt, Jaques, & Stone, 2004; Maffey & Emery, 2006). As a result, no universal screening protocols exist that can be applied to all sports. In addition, the screening tests need to be valid, reliable, cost-effective, and practically viable for implementing in a sports setting (Garrick, 2004; Maffey & Emery, 2006).

Injuries to hamstring, groin, and calf muscles are among the most common injuries in Australian football (Orchard et al., 2013b). Musculoskeletal screening tests implemented by AFL clubs attempt to monitor some of the intrinsic risk factors associated with these injuries (Gabbe, Bennell, Wajswelner, & Finch, 2004; Taylor, Pizzari, & Cook, 2015). The relationship between risk of injury and hamstring flexibility, calf flexibility, and groin strength will be discussed in the following section.

2.4.2 Musculoskeletal screening and the risk of injury

2.4.2.1 Hamstring flexibility

Flexibility is defined as the ability of muscle and tendon to lengthen, and is generally measured through the range of motion in the corresponding joints (Gleim & McHugh, 1997). Hamstring flexibility has attracted much attention as a potential intrinsic risk factor for hamstring injuries. The terminal swing phase of running is a high risk phase for sustaining a hamstring strain (Liu, Sun, Zhu, & Yu, 2017; Picerno, 2017). The two-joint-portion of the hamstring lengthens over both the hip and knee joints during the swing phase, and an eccentric hamstring contraction is required to control the forward momentum of the leg during late swing (Sun et al., 2015). It has been traditionally speculated that greater hamstring flexibility allows for absorption of the hamstring lengthening forces over

a greater distance and for a longer period of time by the elastic components of the muscle, resulting in a lower risk of hamstring injury (Wilson, Wood, & Elliott, 1991; Worrell, Smith, & Winegardner, 1994). While such speculations are theoretically plausible, they are yet to be supported by scientific evidence.

Table 2.5 summarizes prospective studies that have evaluated the role of hamstring flexibility as an intrinsic injury risk factor. As a general theme, hamstring flexibility was measured at some point during the pre-season, and players were then monitored for occurrence of hamstring injuries throughout the competition period. At the end of the study period, comparisons between either the flexibility scores of the injured and uninjured athletes, or the injury risk of athletes with low versus high flexibility were made to determine the influence of hamstring flexibility on the risk of a hamstring injury.

Six of the seven studies presented in Table 2.5 did not find low hamstring flexibility to be an injury risk factor. The only study reporting a substantial relationship between hamstring flexibility and hamstring injuries found the injured players to have approximately 7% lower hamstring flexibility compared to players who did not get injured (small standardized difference of ~ 0.46) (Witvrouw, Danneels, Asselman, D'Have, & Cambier, 2003). It should be noted that the exposure of athletes to training and competition was not recorded and adjusted for in this study, which raises the suspicion of a type I error considering the findings of other studies. In fact, the majority of studies investigating hamstring flexibility as an injury risk factor did not quantify the participants' exposure times to training and competition over the monitoring period, which can potentially affect the outcomes of studies involving a single measurement and extended follow up

periods (Knowles, Marshall, & Guskiewicz, 2006). One interventional study also did not find any beneficial effects for flexibility training in reducing the risk of hamstring injury in elite soccer players (Arnason, Andersen, Holme, Engebretsen, & Bahr, 2008). A number of other studies have evaluated the relationship between hamstring flexibility and risk of injury with a retrospective design, which provide little value (Burkett, 1970; Wallden & Walters, 2005). Areas of inflammation and adhesion occur following muscular injuries, which may negatively affect hamstring flexibility (Garrett Jr, Safran, Seaber, Glisson, & Ribbeck, 1987; Nikolaou, Macdonald, Glisson, Seaber, & Garrett Jr, 1987). Subsequently, studies with a retrospective design are unable to determine whether the hamstring tightness is the predisposing factor or the result of an injury (Bennell, Tully, & Harvey, 1999).

A number of methodological differences existed between the prospective studies summarised in Table 2.5. The participants in these studies ranged from community level to elite level soccer or Australian football players. The stage of pre-season over which the hamstring flexibility is measured can potentially be an important factor, which varies between the studies. The limited available evidence indicates that hamstring flexibility may improve from beginning to the end of pre-season (Caldwell & Peters, 2009). Hamstring flexibility increases by nearly 9% throughout the day (Manire, Kipp, Spencer, & Swank, 2010), however, none of the discussed studies reported on the time of day that the measurements were taken. The method of quantifying hamstring flexibility and the definition of injury also varied between the studies. Injury mechanism was not taken into

account in any of the studies and the number of injury incidences were too small on some occasions.

Considering the discussed issues in regards to timing of the tests as well as the multivariate nature of hamstring injuries (Freckleton & Pizzari, 2012; Prior, Guerin, & Grimmer, 2009), it is not surprising that the majority of studies presented in Table 2.5 did not find a substantial relationship between pre-season hamstring flexibility and the risk of injury. More importantly, the flexibility measures obtained on one occasion during pre-season only reflect the condition of an athlete at that particular time, which may vary throughout the season as a result of exposure to training and competition (Whiteley, 2016). It can be concluded that hamstring flexibility as measured during pre-season does not substantially affect the risk of hamstring injury during the competition period.

Table 2.5. Summary of prospective studies investigating the relationship between hamstring flexibility and the risk of hamstring injury.

| Author (year) | Participants (Injury definition) | Test (timing) | Findings/Comments |
|--------------------------|--|--|---|
| Arnason et al. (2004) | 249 elite and sub-elite soccer players (Training/match time-loss) | Passive knee extension (Once, just before the start of the in-season) | No significant difference between the injured and uninjured groups; p=0.32. Exposure reported as combined training/match time. Considerable difference in the training to match hours ratio between the injured and uninjured group (3.9 vs 22.2). Medical staff who recorded injuries were usually available at matches only. |
| Bennel et al. (1999) | 67 professional and amateur Australian football players (Match time-loss) | Toe-touch (Once, during a 3-4 months pre-season) | No significant difference between the injured and uninjured groups. None of the measures derived from the test was a significant predictor of injury likelihood in a logistic regression analysis. Exact p values, confidence intervals, or relative risks not provided. Small number of hamstring injury incidences (eight). No records of training/match exposure. |

| | | | |
|----------------------------|---|--|---|
| Gabbe et al. (2005) | 126 community level Australian football players (Training/match time-loss and/or required treatment) | Active knee extension, Passive straight leg raise, Sit-and-reach (Once, prior to the pre-season practice matches) | Low hamstring flexibility did not significantly increase the risk of hamstring injury but “approached significance” as assessed by the active knee extension test (relative risk 2.8, 95% confidence interval 0.9-8.5; p=0.076). Interpretation of the results using the confidence limits and magnitude-based inference is indicative of a practically important increase in the risk of injury. The findings may not be applicable to elite athletes. |
| Gabbe et al. (2006) | 222 elite Australian football players (Match time-loss) | Active knee extension, Sit-and-reach (Once, the final 6 weeks of pre-season) | Low hamstring flexibility did not significantly increase the risk of hamstring injury. Wide confidence limits (unclear effect) for the relative risks despite 31 injury incidences. Exposure only measured as the number of matches played. |
| Orchard et al. (1997) | 37 elite Australian football players (Match time-loss) | Sit-and-reach (Once, around the middle of pre-season) | No significant difference between the injured and uninjured groups. Exact p values, confidence intervals, relative risks, or group means not provided. Small number of hamstring injury incidences (six). |
| Rolls and George (2004) | 93 elite youth soccer players (Medical diagnosis only) | Modified sit-and-reach; straight leg raise; active, passive, and | No significant difference between the injured and uninjured groups. Exact p values, confidence intervals, or relative risks not provided. |

| | | | |
|---------------------------|--|---|--|
| | | seated knee extension (Once, end of pre-season) | The difference for active and seated knee extension approached significance while alpha level was conservatively set at 0.01. Injury definition did not specifically include time-loss. |
| Witvrouw et al. (2003) | 146 elite soccer players (Training/match time-loss) | Passive straight leg raise (Once, before the start of the in-season) | The flexibility of the injured group was significantly lower than the uninjured group (p=0.02) Standardized difference could be calculated as ~-0.46 from the provided figure (small standardized difference between groups). |

2.4.2.2 Calf flexibility

Only two studies have evaluated the relationship between calf flexibility and risk of calf injury in field sport athletes (Bradley & Portas, 2007; Witvrouw et al., 2003). The two studies measured the flexibility of calf muscle group in elite soccer players on one occasion at the end of pre-season. Athletes were then monitored for occurrence of injuries (missed training or match time) during the competition period. Calf flexibility was evaluated through goniometric assessment of ankle dorsiflexion range of motion in weight-bearing (Witvrouw et al., 2003) and non-weight-bearing (Bradley & Portas, 2007) positions. Neither of the two studies found a substantial relationship between pre-season calf flexibility and in-season calf injuries. A critical limitation of these studies was the small number of calf injuries (5 and 10), which does not allow for detection of small effects (Hopkins, 2006c). The incidence rate of calf injuries is more than three times lower than that of hamstring injuries in field sport athletes (Hägglund & Waldén, 2012; Orchard et al., 2013b). Accordingly, studies investigating calf injuries need to have considerably larger sample sizes compared to hamstring injury studies in order to increase the likelihood of observing clear effects. Overall, definitive conclusions cannot be made about the influence of calf flexibility on calf injuries in field sport athletes; however, the limited available evidence is indicative of a trivial effect.

2.4.2.3 Groin strength

Three studies have evaluated the relationship between groin strength and groin injuries in field sport athletes (Crow et al., 2010; Delahunt, Fitzpatrick, & Blake, 2017; Engebretsen et al., 2010). Two studies focused on pre-season groin strength (Delahunt et al., 2017; Engebretsen et al., 2010) while one study

investigated the weekly changes in groin strength during the competition period (Crow et al., 2010). Weakness of groin muscles during the pre-season was associated with an increased risk of groin injury in a study of 508 amateur soccer players (odds ratio 4.3, 95% CI 1.3-14) (Engebretsen et al., 2010). Importantly, this study accounted for the history of previous groin injuries by conducting a multivariate logistic regression analysis. It should be noted that in this study groin weakness was determined subjectively by ten different clinicians (weak/not weak), which carries the risk of bias. Objectively evaluated groin strength using hand-held dynamometry was not associated with an increased risk of injury, which could be the result of a poor inter-tester reliability (coefficient of variation=20%) associated with the dynamometry in this study.

A recent study of 55 elite Gaelic footballers also found an increased risk of groin injury associated with low groin strength during pre-season (odds ratio 7.8, 95% CI re-calculated from the provided p-value 1.2 to 50) (Delahunt et al., 2017). Groin strength was measured using the adductor squeeze test (pre-inflated sphygmomanometer between the knees). Threshold for high/low groin strength (dichotomization) was set as 225 mmHg using the receiver operating characteristic curves. The larger magnitude of findings in this study compared to the one described earlier is likely the result of not accounting for the effect of history of previous groin injuries. Athletes with a history of groin injury are at a higher risk of a future groin injury and may carry residual strength deficits from the initial injury (Creighton, Shrier, Shultz, Meeuwisse, & Matheson, 2010; Engebretsen et al., 2010).

A survey of AFL clubs' medical and fitness staff revealed a popular belief that loss of groin strength occurs prior to the start of groin pain (Pizzari, Coburn, &

Crow, 2008). This belief was later supported by a study evaluating the relationship between weekly screening of groin strength and onset of groin pain in elite youth Australian footballers (Crow et al., 2010). The authors found strength reductions of approximately 12% in the week of groin pain onset and 6% in the preceding week. The magnitude of reductions were moderate (effect size 0.98, 95% CI 0.20-1.77) and small (0.55, -0.19-1.33), respectively. While this study provides evidence for the merit of groin strength screening as an athlete monitoring and injury prevention tool, it should be noted that this study was conducted with elite youth players of 16-18 years old. There are considerable differences in training load and player management strategies between elite and sub-elite levels as well as junior and senior elite levels of Australian football (Aughey, 2013; Burgess, Naughton, & Norton, 2012), and it is not known to what extent the findings on youth players apply to elite level Australian footballers.

In summary, available evidence is indicative of an association between groin strength and risk of groin injury; however, generalizability of this notion to elite Australian footballers remains unexplored.

2.4.3 Pre-season (pre-participation) screening versus regular screening

Pre-season (pre-participation) screening is the most commonly studied form of screening where a single measurement of a musculoskeletal factor is obtained during the pre-season and analysed against injuries sustained during the following competition period (Bahr, 2016). Evaluation of musculoskeletal factors in this format improves our understanding of the causative factors of various injuries. However, musculoskeletal tests conducted on a single occasion over the pre-season have incorrectly been claimed to be able to predict injuries (Bahr, 2016). Predictive ability of a test is described using measures such as specificity,

sensitivity, positive and negative predictive value, positive and negative likelihood ratio, and receiver operating characteristic curves (Bahr, 2016; Pepe, Janes, Longton, Leisenring, & Newcomb, 2004; Whiteley, 2016). Musculoskeletal screening tests do not possess a high enough predictive ability to be able to practically predict occurrence of injuries. For instance, the pivot shift test, which is considered as good by clinicians, has a positive likelihood ratio of approximately six to ten, while a positive likelihood ratio of over 9000 is required to predict an injury with a practically acceptable accuracy (Whiteley, 2016).

Another major limitation of pre-season screening is that the test scores only reflect the condition of athletes at that particular time. Musculoskeletal characteristics of athletes can change throughout the season as a result of exposure to training and competition as well as occurrence of new injuries or complete resolution of deficits from previous injuries (Creighton et al., 2010; Croisier, 2004; Whiteley, 2016). Regular screening is an alternative approach aimed to capture the changes in musculoskeletal system in response to training.

It has been speculated that the variation in screening scores obtained from regular screening, rather than the absolute values, better reflect the condition of athletes and their response to prescribed training and subsequently the risk of injury (Paul et al., 2014; Thorpe et al., 2017). The concept of evaluation of change in a repeatedly measured variable has been studied and applied to various measures of recovery such as wellness scores, counter movement jumps, and hormonal markers (Taylor et al., 2012; Thorpe et al., 2017). While regular musculoskeletal screening has been making inroads in elite sports as an athlete monitoring and injury prevention tool over the past few years (Morgan, Poulos, Wallace, Bode, & Buchheit, 2014; Taylor et al., 2012; Thorpe et al., 2017), little

research has been conducted evaluating the normal variability of the screening scores as well as the relationship between detrimental changes in scores and risk of injury. These areas are further explored in Chapter 4 (study 2) and Chapter 5 (study 3) of this thesis.

2.5 History of previous injuries

History of previous injuries is an established injury risk factor. Athletes who have been injured before are at an increased risk of sustaining not only the same injury to the same site, but also injuries to other areas of the body (Fulton et al., 2014; Toohey, Drew, Cook, Finch, & Gaida, 2017). Hence, history of previous injuries has been evaluated from two main perspectives; these being recurrent and subsequent injuries. Recurrent injuries are of the same type and to the same location as the index (initial) injury, while subsequent injuries may differ in nature or location to the index injury (Finch & Cook, 2014; Finch, Cook, Kunstler, Akram, & Orchard, 2017). Subsequent injuries are in fact more common than recurrent injuries in elite Australian footballers (Finch et al., 2017).

Differences in the definition of the index (initial) and subsequent/recurrent injury exists between studies that have evaluated history of previous injuries as an injury risk factor (Table 2.6). The term “previous” that refers to the index injury has encompassed periods ranging from the past season (Hägglund et al., 2006, 2013) to the entire career of athletes (Orchard, Seward, McGivern, & Hood, 2001; Waldén, Hägglund, & Ekstrand, 2006). The definition of the term “injuries” has also been inconsistent between studies and included training/match time-loss, match-only time-loss, or unspecified in some cases for the index injury (Table 2.6). In addition, in some studies, a retrospective approach has been used to record previous injuries, which carries a risk of recall bias (Gabbe, Finch, Bennell, & Wajswelner, 2003). Despite the differences between studies presented in Table 2.6 in the definition of the index and recurrent/subsequent injury, the majority of findings indicate that history of a previous injury is associated with a 1.5 to 4 times higher risk of recurrent or subsequent injuries in elite/professional football code

athletes (Gabbe, Bennell, Finch, Wajswelner, & Orchard, 2006; Hägglund et al., 2006, 2013; Orchard, 2001; Orchard et al., 2001; Waldén et al., 2006).

Possible mechanisms behind the associations between previous injuries and the risk of subsequent injuries typically include reduced muscular strength, flexibility, proprioception, and general fitness, as well as altered running biomechanics and motor control (Dauty, Potiron-Josse, & Rochcongar, 2003; Lee, Reid, Elliott, & Lloyd, 2009; Maniar, Shield, Williams, Timmins, & Opar, 2016; Mujika & Padilla, 2000; Opar et al., 2015). Eccentric hamstring peak torque is reduced in the limb with a previous hamstring injury (Lee et al., 2009), while low eccentric hamstring strength is associated with an increased risk of future hamstring injuries (Opar et al., 2015). The injury-induced detraining results in reductions in aerobic fitness (Mujika & Padilla, 2000), which is a risk factor for future injuries (Gastin, Meyer, Huntsman, & Cook, 2014). Resolution of deficits caused by an injury episode may extend beyond the time of return to play (Orchard & Best, 2002; Verrall, Kalairajah, Slavotinek, & Spriggins, 2006), which will in turn predispose athletes to subsequent injuries (Toohey et al., 2017). It should also be noted that the resolution of some of the injury-induced deficits are time-dependent. For example, hamstring flexibility and isometric strength in the hamstring-injured leg, return to the level of the contralateral un-injured leg on average within 50 and 20 days, respectively, while deficits in dynamic measures of hamstring strength tend to persist for prolonged periods following return to play (Maniar et al., 2016). There are indeed advantages and limitations to various strength testing modalities, which should be considered but are outside the scopes of this thesis. Nevertheless, the gradual resolution of deficits resulting from an injury episode is indicative of decaying effects for history of previous injuries as an injury risk

factor; however, the decaying effects of history of previous injuries on the risk of subsequent/recurrent injuries have rarely been investigated. It should also be acknowledged that history of previous injuries may simply be a marker of athletes who are generally injury-prone, rather than a risk factor with causative effects (Hamilton, Meeuwisse, Emery, Steele, & Shrier, 2011).

The only two studies differentiating between recent and past injuries, found effects of up to four times larger for recent compared to past injuries on the increased risk of recurrent and subsequent injuries (Table 2.6) (Orchard, 2001; Orchard et al., 2001). The definition of “recent” varied considerably between the two studies (<8 weeks vs. <12 months), due to the different nature of the investigated injuries (muscle strain vs. ACL). A steady decline in the risk of recurrence for muscular strains has also been reported over periods of up to 22 weeks following the index injury in elite Australian footballers (Orchard & Best, 2002).

The effects of previous injuries and in particular their decaying nature have been overlooked in recent years, especially among studies investigating the effects of training load on the risk of injury. An injury episode may result in low chronic load and hence reduced fitness upon return to play (Mujika & Padilla, 2000; Toohey et al., 2017). Indeed, low chronic load at early stages of return to play, is only one of multiple mechanisms that explain the effects of previous injuries. Considering the well-established role of previous injuries as an injury risk factor and the likely interactions with training load, the decaying effects of previous injuries should be accounted for in evaluation of the relationship between training load and risk of injury.

Table 2.6. Summary of studies investigating the effects of previous injuries on the risk of recurrent or subsequent injuries in elite/professional football code athletes.

| Author (year) | Participants | Definition of history of previous injuries | Index injury site | Recurrent or subsequent injury site | Effect of a previous injury ^a |
|----------------------|---------------------------------------|--|-------------------|-------------------------------------|--|
| Gabbe et al. 2006 | 222 elite Australian football players | Injuries of unclear definition in the past 12 months recorded through self-reported questionnaires prior to the competition period | Hamstring | Hamstring | Relative risk (95% CI) 4.30 (1.66-11.15) |
| Hagglund et al. 2006 | 197 elite soccer players | Training/match time-loss injuries in the previous season recorded prospectively by medical staff | Any | Any | Hazard ratio (95% CI) 2.7 (1.7-4.3) |
| | | | Hamstring | Hamstring | Hazard ratio (95% CI) 3.5 (1.9-6.5) |
| | | | Groin | Groin | Hazard ratio (95% CI) 2.4 (1.2-4.6) |
| | | | Knee | Knee | Hazard ratio (95% CI) 3.1 (1.3-7.6) |
| | | | Ankle | Ankle | Hazard ratio (95% CI) 3.0 (0.9-10.4) |
| Hagglund et al. 2013 | 1401 professional soccer players | Training/match time-loss injuries in the previous season recorded prospectively by medical staff | Groin | Groin | Hazard ratio (95% CI) 1.40 (1.00-1.96) |
| | | | Groin | Quadriceps | Hazard ratio (95% CI) 1.68 (1.16-2.41) |
| | | | Groin | Calf | Hazard ratio (95% CI) 1.71 (1.15-2.55) |
| | | | Hamstring | Hamstring | Hazard ratio (95% CI) 1.40 (1.12-1.75) |
| | | | Hamstring | Calf | Hazard ratio (95% CI) 1.74 (1.44-2.44) |
| | | | Quadriceps | Quadriceps | Hazard ratio (95% CI) 3.10 (2.21-4.36) |
| | | | Calf | Calf | Hazard ratio (95% CI) 2.33 (1.52-3.57) |
| | | | Calf | Quadriceps | Hazard ratio (95% CI) 1.91 (1.24-2.93) |

| | | | | | |
|------------------------|--|---|---------------------|----------------------|--|
| Opar et al. 2015 | 210 elite Australian football players | Injuries of unclear definition in the past 12 months for hamstring and over entire career for ACL recorded through questionnaires filled by medical staff | Hamstring | Hamstring | Relative risk (95% CI) 2.1 (1.0-4.3) |
| | | | ACL | Hamstring | Relative risk (95% CI) 2.2 (0.9-5.1) |
| Orchard et al. 2001 | 1643 elite Australian football players | Past (>previous 12 months) and recent (within previous 12 months) ACL injuries that required reconstruction recorded through AFL injury surveillance system | ACL (recent) | ACL | Relative risk (95% CI) 11.33 (4.02-31.91) |
| | | | ACL (past) | ACL | Relative risk (95% CI) 4.44 (2.46-8.01) |
| Orchard 2001 | 1607 elite Australian football players | Past (>previous 8 weeks) and recent (within previous 8 weeks) match time-loss injuries recorded through AFL injury surveillance system | Hamstring (recent) | Hamstring | Relative risk (95% CI) 6.33 (5.21-7.70) |
| | | | Hamstring (past) | Hamstring | Relative risk (95% CI) 2.42 (2.05-2.85) |
| | | | Hamstring (recent) | Quadriceps | Relative risk (95% CI) 2.08 (1.12-3.86) |
| | | | Quadriceps (recent) | Quadriceps | Relative risk (95% CI) 15.61 (10.27-23.74) |
| | | | Quadriceps (past) | Quadriceps | Relative risk (95% CI) 3.67 (2.60-5.19) |
| | | | Quadriceps (past) | Calf | Relative risk (95% CI) 1.74 (1.14-2.67) |
| | | | Calf (recent) | Calf | Relative risk (95% CI) 8.94 (5.10-15.66) |
| | | | Calf (past) | Calf | Relative risk (95% CI) 4.28 (2.91-6.29) |
| Calf (past) | Hamstring | Relative risk (95% CI) 1.37 (1.08-1.76) | | | |
| Walden et al. 2006 | 310 professional soccer players | Surgically and non-surgically treated ACL injuries over the entire career of players recorded through self-reports, team doctors and team medical records, and an insurance company | ACL | Knee | Relative risk (95% CI) 3.4 (1.8-6.3) |
| | | | ACL | Knee (excluding ACL) | Relative risk (95% CI) 2.20 (1.62-3.36) ^b |

^aEffects are calculated as the risk for players with a history of a previous injury relative to the risk for players without a history of a previous injury. Only substantial effects are shown.

^bCalculated in a meta-analysis (Toohey et al. 2017).

2.6 Subjective wellness

Subjective wellness refers to various measures of perceived physical and psychological well-being that are self-reported by athletes (Saw, Main, & Gastin, 2015). The low cost, ease of implementation, and superior sensitivity and consistency of the subjective measures compared to the objective methods have made subjective wellness a popular and cost-effective option for monitoring the response to training in elite team sport athletes (Saw et al., 2015; Taylor et al., 2012; Thorpe et al., 2017). A variety of athlete self-report measures and questionnaires including the profile of mood state (POMS) (Buchheit, 2015; Raglin & Morgan, 1994) and the recovery–stress questionnaire for athletes (RESTQ-sport) (Coutts & Reaburn, 2008; Kellmann, 2010; Kellmann & Kallus, 2001) have been developed and utilized in the literature. However, the standard questionnaires are often extensive and time-consuming to complete, which prevents them from being used on a daily basis in team sport environments (Thorpe et al., 2017). Subsequently, sports clubs usually modify the standard questionnaires to develop shorter versions that are specific to their needs, and implement them in their day-to-day athlete monitoring practices (Gastin, Meyer, & Robinson, 2013; Taylor et al., 2012). These customised questionnaires usually consist of 4-12 items that are rated on a Likert scale and typically include fatigue, stress, mood, sleep quality, and muscle soreness (Gastin, Meyer, et al., 2013; Thorpe et al., 2017). These subjective measures are sensitive to daily, within-weekly, and seasonal changes in training load in elite Australian football and soccer (Buchheit et al., 2013; Gallo, Cormack, Gabbett, & Lorenzen, 2017; Gastin, Meyer, et al., 2013; Thorpe et al., 2017). A reduction in overall well-being

score (<7.25 AU) in the presence of increased internal load have also been found to be a contributor to occurrence of illness in professional rugby league players (Thornton et al., 2016). The relationship between subjective wellness scores and risk of injury however, has rarely been investigated. A recent study did not find a relationship between substantial reductions in measures of subjective wellness and risk of injury in elite Australian footballers (Colby, Dawson, Peeling, et al., 2017). In this study, a substantial reduction was defined as a >1 rolling season-to-date SD. A limitation of calculating the SD using the rolling season-to-date approach is that in the absence of enough historical data, inconsistent z-scores may be derived at early stages of the season (Robertson et al., 2017), which could have affected the findings of this study. In addition, it is not clear whether the presence/strength of associations could change by increasing the threshold for the definition of substantial reductions (e.g. >1.5 SD). The relationship between substantial reductions in subjective wellness scores and risk of injury was evaluated in study 3 of this thesis (Chapter 5). Both reduction thresholds of $>1SD$ and >1.5 SD were evaluated and calculated using the pool of data rather than the rolling season-to-date approach.

2.7 Age

Chronological and professional age have frequently been evaluated as an injury risk factor in the literature with mixed findings. While professional age (experience) has mostly been evaluated in studies of Australian football (Colby, Dawson, Peeling, et al., 2017; Fortington et al., 2016; Rogalski et al., 2013), chronological age has received more attention in studies of other football codes (Arnason et al., 2004; Hägglund et al., 2013; Hulin, Gabbett, Caputi, et al., 2016; Verrall, Slavotinek, Barnes, Fon, & Spriggins, 2001). The reason behind the more common application of professional age as opposed to chronological age in Australian football is that most Australian football players are drafted into the professional system at the age of 18-19, and may not have the physical maturity required for training and game intensity at professional level (Burgess et al., 2012; Fortington et al., 2016). The first two seasons at professional level of Australian football are typically considered as the development stage, and categorization of players based on their professional age allows practitioners to better plan for the unique challenges and requirements of this stage (Fortington et al., 2016; Rogalski et al., 2013; Stares et al., 2018). Nevertheless, it can be safely speculated that chronological and professional age are highly correlated.

The majority of studies investigating age as an injury risk factor have reported substantial associations between increasing age and higher risk of injury in elite football code athletes (Arnason et al., 2004; Colby, Dawson, Peeling, et al., 2017; Gabbe, Bennell, Finch, et al., 2006; Hägglund et al., 2013; Henderson, Barnes, & Portas, 2010; Orchard, 2001; Rogalski et al., 2013; Verrall et al., 2001). It has been hypothesized that the body's adaptive capacity in response to a training

stimulus as well as the ability to recover from fatigue diminish with increase in age (Maffey & Emery, 2007); however, little quality evidence specific to athletes exists to support these plausible speculations.

In contrast to the discussed association between increasing age and higher risk of injury, several studies have found no relationships between age and injury risk (Colby et al., 2014; Hägglund et al., 2006; Hulin, Gabbett, Caputi, et al., 2016; Ruddy et al., 2016), or have identified associations between younger age and higher injury risk (Duhig et al., 2016; Fortington et al., 2016). A possible reason behind the inconsistencies between the findings for age as a risk factor is the differences between sports clubs in age-driven interventions and decisions that affect individual athletes. For example, the training load of first year Australian football players may be strictly modified in order to facilitate a smooth transition to the professional level for these players (Rogalski et al., 2013). On the other hand, the best starting players are usually older and tend to have more accelerated returns to competition from injury, which renders them at an increased risk of subsequent injuries (Rogalski et al., 2013; Young et al., 2005). A further complication is the confounding effects of previous injuries where older players are more likely to have experienced injuries with long-lasting implications (Arnason et al., 2004).

A second reason for the observed inconsistencies is the possibility of a non-linear relationship between age and injury risk, where athletes are at a higher risk of injury at both early and late stages of their professional career (Orchard, Seward, & Orchard, 2013a). The possible U-shape relationship between age and injury risk could have been masked in the discussed studies owing to the implemented

injury prevention strategies in their respective elite sports settings; in which case it can be concluded that such preventive measures have been more successful in mitigating the risk for younger compared to older athletes. In the current thesis, professional age (experience) was therefore evaluated as a potential injury risk factor with possible non-linear effects (Chapter 5).

2.8 Aims of the thesis

The primary aim of this thesis was to evaluate the individual and combined effects of multiple factors on the risk of injury in elite team sport athletes. The secondary aim was to evaluate some of the musculoskeletal responses of elite Australian footballers to regular exposure to training and competition. The following studies were designed with the intention of addressing these aims:

- Effects of training load and leg dominance on Achilles and patellar tendon structure
 - How does the structure of Achilles and patellar tendons of elite Australian footballers change over the pre-season training period
 - To what extent the overall training load of pre-season affect the changes in Achilles and patellar tendon structure?
 - Are there any differences between the dominant and non-dominant sides in structural changes of the tendons and the influence of training load?
- Normal variability of weekly musculoskeletal screening scores across an Australian football league season and the influence of training load
 - What is the normal week-to-week variability of the sit-and-reach test, dorsiflexion lunge test, and adductor squeeze test throughout the pre-season and in-season periods?
 - To what extent the normal variabilities differ between individual athletes?
 - To what extent training load affects the weekly screening scores?

- The individual and combined effects of multiple factors on the risk of soft tissue non-contact injuries in elite team sport athletes
 - What are the individual effects of training load, history of previous injuries, professional experience, weekly musculoskeletal screening, and subjective wellness on the risk of injury in elite team sport athletes?
 - How do combinations of multiple risk factors affect the risk of injury?
 - What are the implications of a combination of multiple risk factors for day-to-day injury prevention decision making in elite sports settings?
 - What is the magnitude of individual differences in injury risk?
 - How do the effects of training load measures derived using non-linear methods (exponentially weighted moving averages) compare to those derived using conventional rolling averages?

Chapter 3 – Study 1: Effects of training load and leg dominance on Achilles and patellar tendon structure

Published:

Esmaeili, A., Stewart, A. M., Hopkins, W. G., Elias, G. P., & Aughey, R. J. (2017). Effects of Training Load and Leg Dominance on Achilles and Patellar Tendon Structure. *International Journal of Sports Physiology and Performance*, 12(Suppl 2), S2-122-126. doi: 10.1123/ijsp.2016-0397

3.1 Introduction

Tendons transfer forces from muscles to bones to facilitate movement. Tendon properties change in response to forces applied to the tendon through training (Wiesinger et al., 2015) and detrimental changes in tendon structure are associated with increased risk of tendinopathies (Docking et al., 2015). Tendon stiffness, elastic modulus, and cross-sectional area are measures of tendon mechanical, material, and (macro)morphological properties, respectively, which generally increase following controlled episodes of increased loading (Wiesinger et al., 2015). Little is known about changes in the internal tendon structure in the form of fibrillar alignment (micromorphology) in response to training.

Traditional assessment of the internal tendon structure using ultrasound imaging requires manual tracking of the ultrasound probe. This approach along with the subjective and qualitative interpretation of the ultrasound images does not allow

for quantification of subtle changes in the tendon structure (Docking et al., 2015; Wiesinger et al., 2015). Ultrasound tissue characterization (UTC) is a novel approach that overcomes these limitations by using an automatic ultrasound-probe-tracking device and dedicated image analysing algorithms (van Schie et al., 2010). The tracking device standardises the transducer tilt, angle, focus, gain, and depth (Rosengarten et al., 2015; van Schie et al., 2010). A software reconstructs and analyses a three-dimensional image of the tendon and quantifies the internal tendon structure based on fibrillar alignment (van Schie et al., 2010).

A recent UTC study reported improved fibrillar alignment in the right Achilles tendons of elite Australian football league (AFL) players over the pre-season (Docking et al., 2016), however, individual training loads were not quantified and the influence on changes in tendon micromorphology is currently unknown. The reported asymmetries between the dominant and non-dominant Achilles and patellar tendons in stiffness, elastic modulus, and cross-sectional area (Bohm et al., 2015; Coupe et al., 2008; Pang & Ying, 2006) also raise the question of the influence of leg dominance on changes in the tendon fibrillar alignment in response to training. The aim of this study was to investigate the influence of training load and leg dominance on changes in the Achilles and patellar tendon structure.

3.2 Methods

3.2.1 Participants

Thirty-seven players of one elite Australian football club agreed to participate in the study. Eleven of the players sustained injuries that resulted in more than one

week of modified training during the study period and were subsequently excluded from the study (none were due to Achilles or patellar tendon injuries). The remaining 26 players (mean age \pm standard deviation; 23.7 ± 3.7) were included in the data analysis. None of the included players had a history of Achilles or patellar tendon injury in the preceding 12 months to data collection.

3.2.2 Design

In this prospective cohort study, the Achilles and patellar tendon structure of both legs of the participants were examined using UTC at the beginning and the end of an 18 week pre-season training. Internal and external training loads of individual players were quantified for the period between the two UTC sessions.

3.2.3 Methodology

Ultrasound Tissue Characterization: The UTC equipment and scanning protocols were as previously described (Docking & Cook, 2015) (Appendix 1). An automatic tracking device moved the ultrasound transducer along the length of the tendon capturing an ultrasound image every 0.2 mm. Layers of ultrasound images were then combined in proprietary software (UTC2010, UTC Imaging) to form a three-dimensional data block of the tendon. Algorithms within the software package analysed the stability of brightness in each pixel across contiguous layers. The structure of the scanned tendon was then quantified as relative percentages of four distinct echo-types, which have previously been verified against histological specimens (van Schie et al., 2010). Echo-type I corresponds with intact, aligned, and continuous bundles; echo-type II represents less continuous, less integer, and waving bundles; echo-type III relates to disorganized and fibrillar tissue; and echo-type IV characterizes amorphous matrix with loose fibrils, cells, or fluid (van

Schie et al., 2010). Changes in the echo-types over the pre-season were analysed with increased echo-type I signifying improvements in tendon structure (Docking et al., 2016).

Training load: The internal training load, monotony, and strain for all training sessions were calculated for individual players using the session rating of perceived exertion (sRPE) method (Foster et al., 2001). A typical training week consisted of three field training, four weight training, three aerobic training, two recovery, and one other conditioning sessions. Two to three days of reduced loading were planned between the days with high training loads. The general structure of pre-season involved a controlled increase in training load followed by a period of relatively reduced loading (weekly loads similar to the competition period) and four pre-season matches towards the end. Indeed some session types that involve high impact weight bearing or lower body weight training, apply larger forces to the Achilles and patellar tendons compared to other sessions (e.g field > recovery); however, since the exact differences are unknown, all session types were pooled to calculate the total individual internal training loads. The external training load was quantified using global positioning system (GPS)/accelerometer units (Optimeye S5, Catapult Innovations, Australia) for every field training session (including the pre-season matches). Total distance covered, Player Load™, and the high intensity running (HIR) distance (>4.17 m.s⁻¹) were extracted from the software (Sprint v5.1.3, Catapult Innovations, Australia) (Aughey, 2010; Boyd et al., 2013).

3.2.4 Statistical analysis

Data were analysed using a custom Microsoft Excel spreadsheet (Hopkins, 2006a). The modifying effects of training load on changes in tendon structure were estimated by including each measure separately as a linear covariate. The effects of training load were calculated for a 2 between-subject standard deviation increase in the load (Hopkins et al., 2009). Standardization and magnitude-based inference with 90% confidence limits were used to describe and interpret the results (Hopkins et al., 2009). Thresholds for interpreting the standardized change/effect (effect size; ES) were as follows: <0.2, trivial; 0.2 to <0.6, small; 0.6 to 1.2, moderate; >1.2, large (Hopkins et al., 2009). The chances of true change/effect (greater than the smallest worthwhile change/effect) were calculated and expressed qualitatively as follows: <0.5%, *most unlikely*; 0.5% to <5%, *very unlikely*; 5% to <25%, *unlikely*; 25% to <75%, *possibly*; 75% to <95%, *likely*; 95% to <99.5%, *very likely*; >99.5%, *most likely*. The true change/effect was assessed as unclear when the chances of positive and negative change/effect were both >5% (Hopkins et al., 2009).

3.3 Results

Achilles and patellar tendons of both sides showed *possibly* to *very likely* small improvements (increases in echo-type I) over the pre-season training period (Figure 3.1). Increased echo-type I coincided with decreases in echo-type II and predominantly trivial or unclear changes in echo-type III and echo-type IV (Figure 3.1) and as a result, all further analysis focused on changes in echo-type I.

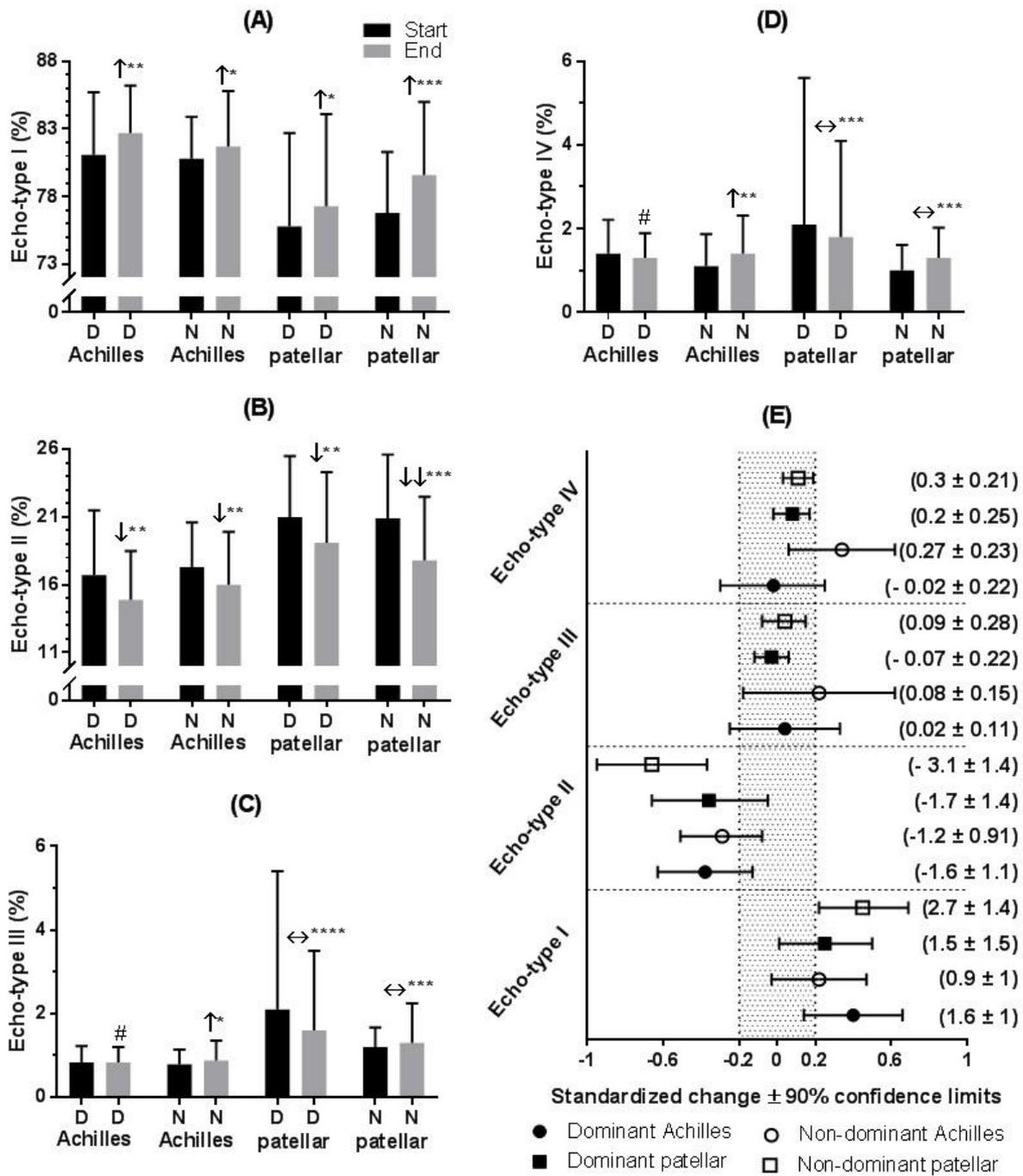


Figure 3.1. Tendon structure at the start and the end of pre-season. (A) echo-type I, (B) echo-type II, (C) echo-type III, (D) echo-type IV, (E) estimated change in the four echo-types over the pre-season. Brackets contain the raw change (%) ± 90% confidence limits.

Notes: D dominant, N non-dominant, ↑ small increase, ↓ small decrease, ↓↓ moderate decrease, ↔ trivial change, # unclear change, * possibly, ** likely, *** very likely, **** most likely.

There were no clear differences between the baseline values of the two sides for either the Achilles (ES 0.09; 90% confidence limits ± 0.34) or patellar (-0.21; ± 0.41) tendons. The improvement in the structure of the dominant Achilles tendon was *possibly* larger than the non-dominant side (0.2; ± 0.32). No clear differences were found between the improvements in the patellar tendons of the two sides (-0.1; ± 0.35).

Training load (Table 3.1) had mostly clear but opposite effects on changes in the Achilles tendon structure of the two sides. Player Load™, total distance, and HIR had *likely* small negative effects on the dominant Achilles tendon while the effects for the sRPE, monotony, and strain were unclear (Figure 3.2-A). Player Load™, sRPE, and strain had *possibly* to *likely* positive effects on the non-dominant Achilles tendon while the effects for the total distance, HIR, and monotony were unclear (Figure 3.2-A). There were *likely* to *very likely* moderate differences between the Achilles tendons of the two sides in the effects of various measures of training load. The normal distribution of training load was not evaluated in this study as they were predictor variables and their distribution was irrelevant to the analysis and findings.

Table 3.1. Average weekly training load and the between-subjects variability for the period between the two ultrasound tissue characterization sessions.

| Measure of training load | Mean \pm SD | Range (Min - Max) |
|--------------------------------|-----------------|----------------------|
| sRPE (AU) | 2212 \pm 190 | 1855 - 2595 |
| Total distance (Km) | 19.1 \pm 1.8 | 16.1 - 22.7 |
| Player Load TM (AU) | 1751 \pm 208 | 1453 - 2200 |
| HIR (Km) | 5.1 \pm 0.8 | 3.6 - 6.6 |
| Monotony (AU) | 0.89 \pm 0.03 | 0.84 – 0.97 |
| Strain (AU) | 2281 \pm 272 | 1808 - 2914 |

SD, standard deviation; AU, arbitrary units; sRPE, session rating of perceived exertion; HIR, high intensity running.

Monotony and HIR were the only measures that had clear *possibly* small positive effects on the changes in the non-dominant patellar tendon structure. All other measures had unclear effects on the patellar tendons of both sides (Figure 3.2-B).

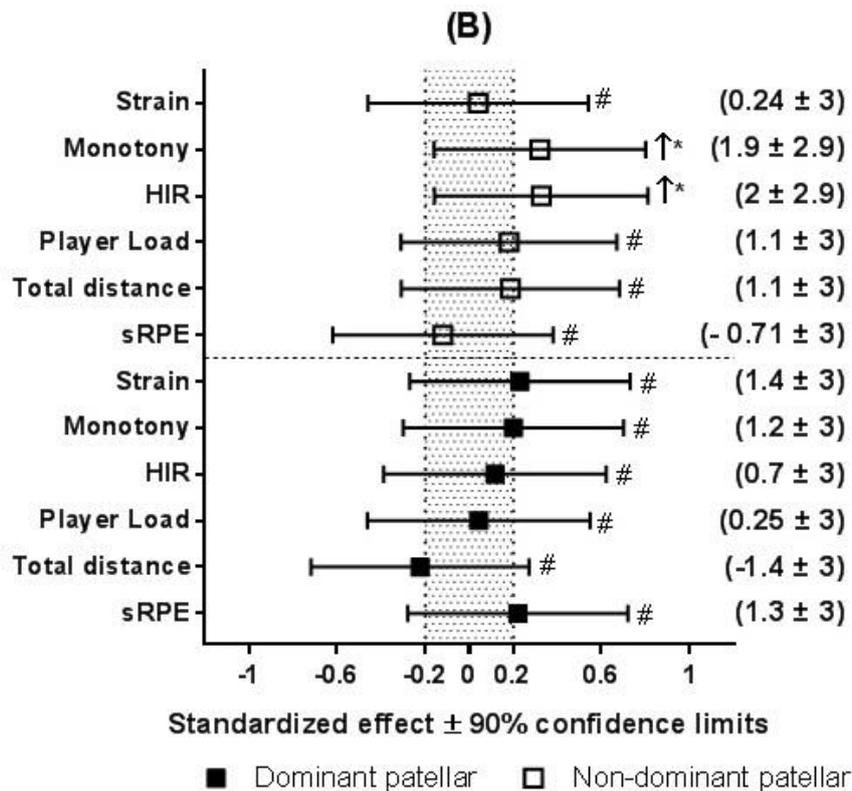
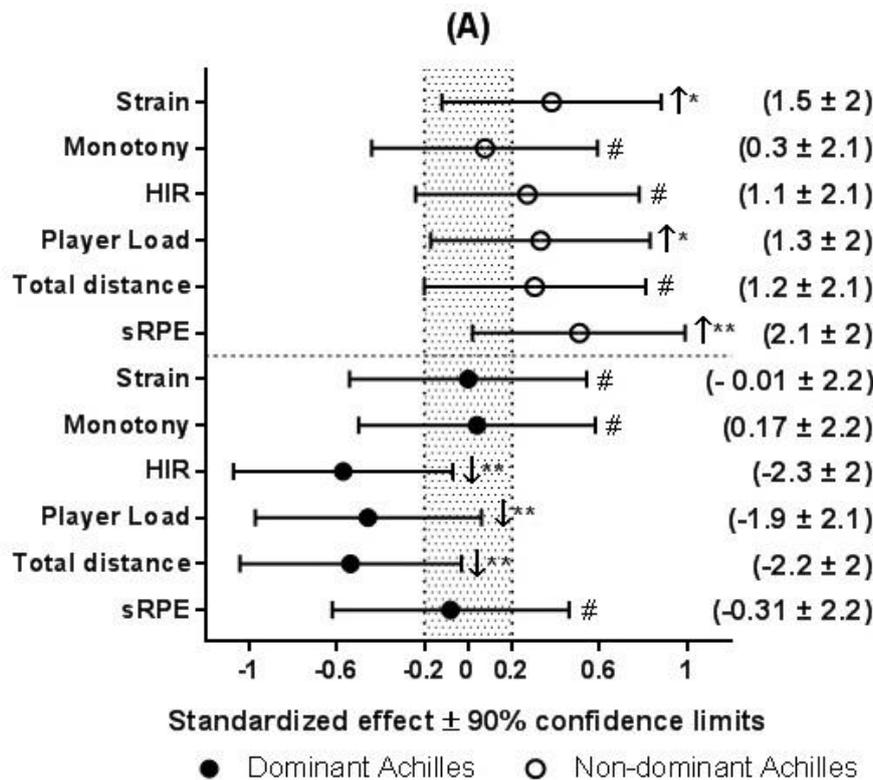


Figure 3.2. Effects of training load on Achilles (A) and patellar (B) tendon structure: Estimated change in echo-type I for a 2 standard deviation increase in training load. Brackets contain the estimated raw change (%) ± 90% confidence limits.

Notes: ↑ small positive effect, ↓ small negative effect, # unclear effect, * possibly, ** likely, sRPE session rating of perceived exertion, HIR high intensity running

3.4 Discussion

The structure of the Achilles and patellar tendons of both sides improved over the pre-season training period while individual training loads had small and inconsistent effects on the changes in tendon structure. The effects were mostly negative on the dominant Achilles tendon, mostly positive on the non-dominant Achilles tendon, and mostly unclear on the patellar tendons of both sides.

Detrimental changes in the normal tendon structure induced by training, are proposed to fall on a continuum that ranges from reactive tendinopathy to tendon disrepair and eventually degenerative tendinopathy (Cook & Purdam, 2009). An episode of acute tendon overloading elicits a proliferative response in the tenocytes and the extra cellular matrix that drives the tendon forward on the pathology continuum (Cook & Purdam, 2009). On the other hand, episodes of reduced loading (recovery) negate such detrimental changes and allow the tendon structure to return back to normal (Cook & Purdam, 2009). Detrimental changes in the Achilles tendon structure that are induced by an AFL match, return to baseline within four days (Rosengarten et al., 2015). The observed small and inconsistent effects of training load in the current study indicate that the amount of training load is not the only driver of the changes in tendon structure over the pre-season and the recovery of tendon structure before the next overloading sessions is a key factor. The Achilles and patellar tendons of AFL players can tolerate high training loads, within the range quantified in this study, provided enough recovery has occurred between two consecutive tendon overloading sessions. Inadequate recovery between training sessions will likely result in

reduced proportions of echo-type I, increases in echo-type II and in more severe/chronic cases increases in echo-types III and IV.

The improvement in the right Achilles tendons of a group of participants from another AFL club (6.1% increase in echo-type I) (Docking et al., 2016) was considerably larger than the observed improvements in the current study (1.6% for the dominant and 0.9% for the non-dominant Achilles tendons) despite the similarities between the two studies in participants' age and athletic level, training period, UTC equipment, and scanning protocols. Differences between the two clubs in training parameters as well as periodization and recovery strategies may have contributed to the differences in the magnitude of findings and further supports the discussed importance of these factors on changes in tendon structure. The abovementioned study excluded players with any training modification, which could have also contributed to their larger magnitude of improvement as well as a higher baseline value for echo-type I (83.2%) compared to the current study (81.1% and 80.8%). Analysis of monotony and strain in the current study could not reflect the role of weekly training periodization as they were averaged for the 18 weeks of pre-season. A weekly repeated measurement of tendon structure modelled against weekly measures of training load may provide a better estimate of the effects of training parameters and periodization on changes in tendon structure.

Leg dominance affected the amount of change in tendon structure as well as the effects of training load for the Achilles tendon but not for the patellar tendon. Discrepancies between the Achilles tendons of the two sides may have arisen from the slightly different loads that go through these tendons due to sport specific

activities. Activities such as the single leg weight bearing phase of kicking and rapid push off at the beginning of acceleration and change of direction are often performed with the non-dominant side and exert large forces on the non-dominant Achilles tendon (Ball, 2013; Clagg, Warnock, & Thomas, 2009; Maffulli, 1999), which could have contributed to the observed differences between the two sides. The positive effect of training load on the non-dominant Achilles tendon may be the result of its long term exposure to such larger forces and its subsequent improved adaptive capacity for a given load compared to the dominant side. Asymmetries in the elastic modulus and cross-sectional area of the dominant and non-dominant Achilles tendons have been reported (Bohm et al., 2015; Pang & Ying, 2006) and we show that asymmetries also exist in the response to training and the effects of training load at the micromorphological level. It should also be acknowledged that such side-to-side differences could simply be due to Type I error; however, the likelihood and magnitude of differences (*likely to very likely moderate*) along with the previously reported asymmetries warrant further investigation into consideration of leg dominance in devising load management strategies for players who are at a higher risk of developing tendinopathies.

3.5 Practical Applications

Regular assessment of tendon structure may flag maladaptation to training in elite footballers.

3.6 Conclusion

The micromorphology (fibrillar alignment) of Achilles and patellar tendons of AFL players improved over the pre-season training period. The small and inconsistent

effects of training load are indicative of the role of recovery between tendon overloading (training) sessions and the multivariate nature of the tendon response to load with leg dominance a possible influencing factor.

Chapter 4 – Study 2: Normal variability of weekly musculoskeletal screening scores and the influence of training load across an Australian Football League season

Published:

Esmaeili, A., Stewart, A. M., Hopkins, W. G., Elias, G. P., Lazarus, B. H., Rowell, A. E., & Aughey, R. J. (2018). Normal variability of weekly musculoskeletal screening scores and the influence of training load across an Australian Football League season. *Frontiers in Physiology, 9*, 144. doi: 10.3389/fphys.2018.00144

4.1 Introduction

Musculoskeletal screening refers to a series of tests designed to detect internal abnormalities that are associated with increased injury risk, or incomplete recovery from training or previous injuries (Bahr, 2016; Dennis, Finch, Elliott, & Farhart, 2008; Morgan et al., 2014). The ultimate aim of screening is to implement effective interventions such as treatments, injury prevention exercises, or training modifications before an injury occurs (Bahr, 2016).

Pre-season (pre-participation) musculoskeletal screening is a widely studied approach where athletes are tested at the start of pre-season and then monitored prospectively for occurrence of injuries for the remainder of the season. Cut scores are then set with the aim of identifying athletes with high injury risk (Bahr, 2016). This approach has been criticised for its poor predictive ability and the risk

of providing a false sense of security (Bahr, 2016; Whiteley, 2016). It has also been argued that pre-season test scores only represent the athlete's condition at that particular time, which may vary throughout the season as a result of exposure to training and competition (Whiteley, 2016).

Repeated-measures or regular screening is another approach that involves frequently conducting testing and measuring the change in screening test scores (Paul et al., 2014). The rationale behind the repeated-measures format is that changes in screening scores better reflect the condition of athletes, how they are responding to training, and subsequent injury risk (Paul et al., 2014; Thorpe et al., 2017). The concept of repeated-measures testing and monitoring of athletes has been applied to the physiological, hormonal, biochemical, psychological, and neuromuscular measures of recovery (Taylor et al., 2012; Thorpe et al., 2017). The repeated-measures musculoskeletal screening strategy for athlete monitoring and injury prevention purposes is gaining momentum in professional sports, however, the underlying evidence to support this approach is very limited.

Injuries to hamstring, groin, and calf muscles are among the most common injuries in Australian football, and the musculoskeletal screening tests implemented by AFL clubs attempt to monitor some of the intrinsic risk factors associated with these injuries (Gabbe et al., 2004; Morgan et al., 2014; Orchard et al., 2013b). Such tests need to be valid, reliable, cost-effective, and easy to implement in a sports setting (Garrick, 2004; Maffey & Emery, 2006). The sit and reach test (S&R), adductor squeeze test (AST), and dorsiflexion lunge test (DLT) are examples of commonly used tests in repeated-measures screening designed to provide measures of lower back and hamstring flexibility, hip adductors'

strength, and calf flexibility (through ankle dorsiflexion range of motion), respectively (Bennell et al., 1998; Gabbe et al., 2004; Malliaras, Hogan, Nawrocki, Crossley, & Schache, 2009). These tests have good to excellent intra-tester reliability with intraclass correlation coefficients (ICC) between 0.81 and 0.98 (Bennell et al., 1998; Gabbe et al., 2004; Malliaras et al., 2009). The standard error of measurement (SEM) was calculated as 1 cm for the S&R, 0.5 to 0.6 cm for the DLT, and 20 mmHg (~10%) for the AST (Bennell et al., 1998; Gabbe et al., 2004; Malliaras et al., 2009). However, these reliability measures have been calculated for only two measurements with test-retest gaps between 30 minutes and one week, and it is not clear to what extent regular exposure to training and competition over extended periods affects these measures. Understanding the normal variability of test scores throughout the season, when athletes are not injured, is a crucial step in identifying the relationship between the changes in test scores, maladaptation to training, and the risk of injuries (Bakken et al., 2017).

Accumulation of training-induced stress on the musculoskeletal system may result in maladaptation and increased risk of injuries (Vanrenterghem et al., 2017). In the absence of direct measurement methods of biomechanical load on body tissues in a field context, indirect methods such as the session rating of perceived exertion (sRPE) have been proposed as viable alternatives (Vanrenterghem et al., 2017). Musculoskeletal measures respond to the acute load of soccer and Australian football matches (Dawson, Gow, Modra, Bishop, & Stewart, 2005; Paul et al., 2014); thus, it is also important to investigate the effects of training load on the possible changes in the test scores. In addition,

individual differences in the normal variability requires investigation in order to develop an effective flagging system based on the changes in scores relative to their normal variability. The aim of this study was to identify the normal variability of a selection of weekly musculoskeletal screening tests and the associated individual differences in variability, as well as the influence of training load on the changes in test scores across an Australian football season.

4.2 Methods

4.2.1 Participants

All the 44 elite male players from one Australian football club were invited and agreed to participate in this study (mean age \pm SD; 22.8 \pm 4.0). The study was approved by Victoria University Human Research Ethics Committee, and all participants provided written informed consent in accordance with the Declaration of Helsinki.

4.2.2 Study design

Weekly musculoskeletal screening scores and daily internal training load were recorded for individual players over an entire Australian football league (AFL) season. Weekly musculoskeletal screening tests were conducted within three hours prior to the first field training session of the week, which was planned two or three days apart from a previous field training session or a match. Based on the club's training schedule, screening occurred on Monday mornings during pre-season and Tuesday afternoons during in-season. This timing was chosen to allow the medical staff to further investigate players with abnormally reduced scores or accompanying symptoms prior to the training session. Pre-season and in-season periods were analysed separately due to the possible effects of diurnal

variation (Manire et al., 2010). The final five weeks of the official pre-season involved match simulations and a pre-season tournament during which the training schedule, training loads, and screening times resembled those of the in-season. As a result, this phase was considered as a part of the in-season for the purposes of this study. Thirty-five screening sessions were held in total (pre-season=8, in-season=27) with no screening on some other weeks due to team unavailability (Christmas break, training camp, and scheduling issues). Individual screening scores were excluded from the analysis when a player was diagnosed as injured by the club's medical staff and could not fully participate in the training session that followed the screening.

4.2.3 Screening tests

Sit and reach test- Players placed their bare feet against the sit and reach box and their middle fingers on top of each other. They were then asked to stretch forward as far as possible and hold the position for one second while keeping the knees straight. The reach distance from the tip of the middle fingers relative to the toe line was recorded (Gabbe et al., 2004).

Dorsiflexion lunge test- A permanent tape measure was fixed on the floor with 0 cm mark at a wall junction. Players were asked to place the big toe and heel of the testing leg beside the tape. They were then instructed to lunge forward until the knee touches the wall while keeping the heel in contact with the floor. The maximum distance from the tip of the big toe to the wall was recorded (Bennell et al., 1998).

Adductor squeeze test- With players in a supine position, a sphygmomanometer cuff pre-inflated to 20 mmHg was placed between the knees. Players were asked to maximally squeeze the cuff and hold for one second and the maximum pressure displayed on the dial was recorded. The test was conducted in three hip flexion angles of 0°, 45°, and 90° (Malliaras et al., 2009).

4.2.4 Training load

The session rating of perceived exertion (sRPE) method was used to quantify the individual internal training load for all training sessions and matches (RPE multiplied by the session duration) (Foster, 1998). The sRPE method has been validated for monitoring training load in Australian football (Scott, Black, et al., 2013). Various cumulative and relative measures of training load were then calculated with each screening day as the reference point. These measures included the 7, 14, 21, and 28 day cumulative loads; monotony; strain; acute to chronic load ratio (mean daily load of the past 7 days divided by the mean daily load of the past 28 days); and the smoothed load (Foster, 1998; Hulin, Gabbett, Lawson, et al., 2016). The smoothed load is an exponentially weighted moving average of training load, which accounts for the decaying effects of training load using a decay factor λ (lambda) (Hunter, 1986; Williams, West, et al., 2017). The smoothed load at the beginning of each day is calculated as $[\lambda \times (\text{yesterday's training load})] + [(1 - \lambda) \times \text{the smoothed load up to that point}]$. The decay factor λ defines a time constant $1/\lambda$ representing the period that contains approximately 2/3 of the total weighting in calculation of the smoothed load. The smoothed load was calculated with decay factors of 0.33, 0.14, 0.07, and 0.036 representing time constants of 3, 7, 14, and 28 days, respectively. It should be noted that the

method of labelling the time constants used in the current study ($1/\lambda$) is slightly different to the one recently suggested $[(2-\lambda)/\lambda]$ (Williams, West, et al., 2017). Using the current method of labelling the time constant, the smoothed load of a given period has the highest correlation with the simple cumulative load of a similar period (Table 4.1).

Table 4.1. Correlations between simple cumulative and smoothed training loads of various periods on a given day^a.

| | Cumulative 3 day | Cumulative 7 day | Cumulative 14 day | Cumulative 21 day | Cumulative 28 day |
|-------------------------|---------------------|---------------------|----------------------|----------------------|----------------------|
| Pre-season ^b | | | | | |
| Smoothed 3 day | 0.91 | 0.81 | 0.63 | 0.39 | 0.18 |
| Smoothed 5 day | 0.83 | 0.91 | 0.81 | 0.58 | 0.33 |
| Smoothed 7 day | 0.73 | 0.90 | 0.89 | 0.71 | 0.46 |
| Smoothed 10 day | 0.60 | 0.81 | 0.91 | 0.82 | 0.61 |
| Smoothed 14 day | 0.46 | 0.67 | 0.86 | 0.86 | 0.72 |
| Smoothed 21 day | 0.32 | 0.48 | 0.68 | 0.77 | 0.75 |
| Smoothed 28 day | 0.24 | 0.36 | 0.52 | 0.62 | 0.65 |
| In-season ^c | | | | | |
| Smoothed 3 day | 0.85 | 0.70 | 0.59 | 0.48 | 0.42 |
| Smoothed 5 day | 0.81 | 0.82 | 0.77 | 0.66 | 0.59 |
| Smoothed 7 day | 0.75 | 0.84 | 0.86 | 0.78 | 0.72 |
| Smoothed 10 day | 0.66 | 0.81 | 0.90 | 0.87 | 0.83 |
| Smoothed 14 day | 0.57 | 0.75 | 0.90 | 0.92 | 0.90 |
| Smoothed 21 day | 0.46 | 0.66 | 0.84 | 0.90 | 0.93 |
| Smoothed 28 day | 0.40 | 0.58 | 0.77 | 0.86 | 0.91 |

^aValues are Pearson correlation coefficients. The highest value of each row is in bold.

^bThe number of observations for training load measures ranged from 3271 (cumulative 28 day) to 4503 (smoothed loads).

^cThe number of observations was 8800 for each training load measure. Unlike the pre-season phase, all measures could be calculated from the first day of the in-season.

4.2.5 Statistical analysis

The analyses were performed in three parts using the Statistical Analysis System (version 9.4, SAS Institute, Cary, NC). Based on the scale of the test scores, only the AST scores were log-transformed before modelling (Hopkins et al., 2009). In

the first part, each individual's within-subject variability of test scores in each season phase was derived separately as the standard error of the estimate (SEE) of the scores using a general linear mixed model that included a linear trend over each phase. The mean of the individual SEEs represented the normal variability of the scores over each phase (a reasonable estimate of SEM for comparison purposes considering the observed trivial trends). The individual SEEs were then analysed in a meta-analytic mixed model with a random effect representing true differences between the individual SEEs and expressed as a factor SD. The difference between individuals with typically high variability (mean SEE \times factor SD) and low variability (mean SEE \div factor SD) was used to assess the magnitude of the individual differences in variability (Hopkins, 2015; Smith & Hopkins, 2011).

In the second part, another general linear mixed model was devised to identify any possible linear trends in the scores at each phase by including the week as a numeric fixed effect. The week number and player identity were defined as nominal random effects. A model in which a different variability (the residual) was specified for each player failed to converge for any of the tests. To account for the real differences in variability, the players were therefore assigned to three subgroups of low, moderate, and high variability based on the findings of the previous part, with a separate residual for each subgroup. A dummy variable for the number of days post-match that the screening occurred (two or three) was added to the model. This dummy variable was used to compare the within-subject differences in the scores as a result of an extra recovery day post-match.

In the third part, a quadratic mixed model was developed to evaluate the effects of various measures of training load on the screening scores. The intercept, training load measure, and the square of the training load measure were the fixed effects, which collectively estimated the mean quadratic. The random effects were player identity (to estimate different between-player means across each season phase), the interaction of player identity with the training measure and with the square of the training measure (to estimate individual differences in the players' quadratics), and the residual error (within-player week-to-week variability). This model estimated the within-subject changes in a given screening score associated with within-subject changes in a given measure of training load. Within-player SDs of training load in each season phase were therefore used to estimate the magnitude of effects. The scores were estimated at typically very low (-2SD), low (-1SD), mean, high (+1SD), and very high (+2SD) values of training load. On the few occasions where -2SD of training load was a negative value, the estimates for the screening scores were calculated for zero training load. Uncertainty in the estimate of the turning point of the quadratic curve was determined via parametric bootstrapping (Hébert-Losier, Platt, & Hopkins, 2015). The turning points were mostly unclear (>10% of the bootstrap samples had quadratic curvature opposite to the observed curvature) because the effect of training on the test scores was approximately linear. Hence, a 2SD difference in the predictor (from -1SD to +1SD) was used to quantify the magnitude of the effects of training load (Hopkins et al., 2009).

The findings were interpreted using mechanistic magnitude-based inference (Hopkins et al., 2009). The uncertainty in estimates was expressed as 90%

confidence limits (CL) and qualitatively as chances that the true value of the estimate was either trivial or substantial (larger than the smallest important change) using the following scale: <0.5%, *most unlikely*; 0.5% to <5%, *very unlikely*; 5% to <25%, *unlikely*; 25% to <75%, *possibly*; 75% to <95%, *likely*; 95% to <99.5%, *very likely*; >99.5%, *most likely*. The true change was deemed unclear when the chances of substantial positive and negative change were both >5% (Hopkins et al., 2009). The smallest important change for the AST was calculated as 0.2 of the observed between-subject SD (Hopkins et al., 2009). The raw S&R and DLT scores are influenced by anthropometry, and differences between individuals may not be due to real differences in flexibility and range of motion (Bennell et al., 1998; Hopkins & Hoeger, 1992). Consequently, a smallest important change of 1 cm was selected for these tests, based on clinical experience. Smallest important changes were halved for interpretation of magnitude of SDs representing variability (Hopkins, 2015; Smith & Hopkins, 2011). Changes representing trivial, small, moderate and large magnitudes were consistent with those provided by standardization (<1x, 1x, 3x and 6x the smallest important change, respectively) (Hopkins et al., 2009).

4.3 Results

The findings for the left and right DLTs were nearly identical as were the findings for the three ASTs. Hence, only the results for the right DLT and AST at 0 degrees of hip flexion are shown. One player sustained a season-ending injury at the end of pre-season and was excluded from the in-season analysis. Table 4.2 summarizes the statistics derived from the first and second parts of the analysis. Substantial small to moderate variability was found for all the tests at both pre-

season and in-season when players were cleared to fully participate in the training session that followed the screening. *Likely* to *very likely* small individual differences in variability existed for the S&R and AST. The only substantial trend was a *very likely* small increase in the AST over the in-season. Not shown in the table are the differences between the scores when the screening was conducted at three days versus two days post-match (Saturday versus Sunday match); these were all *most likely* trivial (for example, the difference for the AST was -0.6%, 90% CL \pm 1.2%).

The effects of an increase in training load from -1SD to +1SD on the screening scores are shown in Table 4.3. Figure 4.1, Figure 4.2, and Figure 4.3 show the changes in screening scores with changes in training load over a wider range (-2SD to +2SD). All measures of training load had trivial effects on the screening scores at both pre-season and in-season.

Table 4.2. Statistics summarizing screening test scores for an AFL team in a pre- and in-season phase derived from parts one and two of the analysis.

| | Statistics from reliability analysis allowing for linear trend in each phase | | | Statistics from meta-analysis of individual values of within-subject variability (SEE) | |
|------------------------------|--|---|---------------------------------------|--|---|
| | Mean \pm between-subject SD in a typical test | Trend over the season phase; $\pm 90\%$ CL | Intraclass correlation; $\pm 90\%$ CL | Mean variability; $\pm 90\%$ CL | Individual differences in variability as factor SD ^a ; $\times/\div 90\%$ CL |
| Sit and reach test (cm) | | | | | |
| Pre-season | 2.3 \pm 8.2 | 0.21; ± 0.24 ^{ML\leftrightarrow} | 0.98; ± 0.01 | 0.92; ± 0.14 ^{ML\downarrow} | 1.66; $\times/\div 1.12$ ^{VL\downarrow} |
| In-season | 3.1 \pm 7.9 | 0.03 ± 0.23 ^{ML\leftrightarrow} | 0.97; ± 0.01 | 1.01; ± 0.12 ^{ML\downarrow} | 1.52; $\times/\div 1.09$ ^{VL\downarrow} |
| Dorsiflexion lunge test (cm) | | | | | |
| Pre-season | 11.4 \pm 3.2 | -0.05; ± 0.14 ^{ML\leftrightarrow} | 0.97; ± 0.01 | 0.50; ± 0.08 ^{P\downarrow} | 1.43; $\times/\div 1.15$ ^{L\leftrightarrow} |
| In-season | 11.3 \pm 3.3 | -0.05; ± 0.09 ^{ML\leftrightarrow} | 0.96; ± 0.01 | 0.48; ± 0.06 ^{P\downarrow} | 1.37; $\times/\div 1.10$ ^{L\leftrightarrow} |
| Adductor squeeze test | | | | | |
| Pre-season | 253 mmHg \pm 20% | 0.4%; $\pm 2.9\%$ ^{ML\leftrightarrow} | 0.74; ± 0.08 | 7.8%; $\pm 0.8\%$ ^{ML$\uparrow\uparrow$} | 1.38; $\times/\div 1.10$ ^{VL\downarrow} |
| In-season | 266 mmHg \pm 21% | 6.5%; $\pm 2.2\%$ ^{VL\uparrow} | 0.81; ± 0.07 | 7.4%; $\pm 0.6\%$ ^{ML$\uparrow\uparrow$} | 1.31; $\times/\div 1.07$ ^{L\downarrow} |

^aMultiply and divide the mean variability by this factor to get typically high and low individual values of the variability.

AFL, Australian football league; SD, standard deviation; SEE, standard error of the estimate; CL, confidence limits.

Likelihood: P, *possibly*; L, *likely*; VL, *very likely*; ML, *most likely*.

Magnitude of variability: \leftrightarrow trivial; \uparrow small; $\uparrow\uparrow$ moderate.

Magnitude of trend: \leftrightarrow trivial; \uparrow small increase.

Table 4.3. Effects of training load on the test scores derived from part three of the analysis.

| Training load measure | Mean \pm within-subject SD | Effect of an increase in training load from -1SD to +1SD ^a | | |
|--------------------------|------------------------------|---|--|--------------------------------------|
| | | S&R; \pm 90% CL (cm) | DLT; \pm 90% CL (cm) | AST; \pm 90% CL (%) |
| Pre-season (n=44) | | | | |
| Cumulative 3 day | 410 \pm 380 | -0.09; \pm 0.17 ML \leftrightarrow | -0.07; \pm 0.07 ML \leftrightarrow | 1.1; \pm 1.6 ML \leftrightarrow |
| Cumulative 7 day | 2440 \pm 1260 | -0.18; \pm 0.20 ML \leftrightarrow | -0.07; \pm 0.10 ML \leftrightarrow | 0.4; \pm 1.9 ML \leftrightarrow |
| Cumulative 14 day | 4260 \pm 2160 | -0.13; \pm 0.20 ML \leftrightarrow | -0.05; \pm 0.10 ML \leftrightarrow | 1.8; \pm 1.9 VL \leftrightarrow |
| Cumulative 28 day | 8120 \pm 2300 | 0.02; \pm 0.17 ML \leftrightarrow | -0.01; \pm 0.05 ML \leftrightarrow | 0.6; \pm 1.8 ML \leftrightarrow |
| Smoothed 3 day | 210 \pm 120 | -0.12; \pm 0.19 ML \leftrightarrow | -0.05; \pm 0.09 ML \leftrightarrow | 0.3; \pm 1.9 ML \leftrightarrow |
| Smoothed 7 day | 280 \pm 120 | -0.16; \pm 0.22 ML \leftrightarrow | -0.04; \pm 0.10 ML \leftrightarrow | 0.5; \pm 2.0 VL \leftrightarrow |
| Smoothed 14 day | 300 \pm 90 | -0.06; \pm 0.18 ML \leftrightarrow | -0.03; \pm 0.10 ML \leftrightarrow | 1.0; \pm 1.8 VL \leftrightarrow |
| Smoothed 28 day | 330 \pm 90 | -0.09; \pm 0.20 ML \leftrightarrow | -0.11; \pm 0.15 ML \leftrightarrow | 1.4; \pm 2.0 VL \leftrightarrow |
| Acute:Chronic ratio | 1.20 \pm 0.80 | -0.11; \pm 0.17 ML \leftrightarrow | -0.05; \pm 0.07 ML \leftrightarrow | 0.8; \pm 1.7 ML \leftrightarrow |
| Monotony | 0.86 \pm 0.22 | -0.30; \pm 0.25 ML \leftrightarrow | -0.04; \pm 0.10 ML \leftrightarrow | 0.7; \pm 2.2 VL \leftrightarrow |
| Strain | 2560 \pm 1150 | -0.30; \pm 0.21 ML \leftrightarrow | -0.07; \pm 0.09 ML \leftrightarrow | -0.1; \pm 1.7 ML \leftrightarrow |
| In-season (n=43) | | | | |
| Cumulative 3 day | 950 \pm 360 | 0.08; \pm 0.14 ML \leftrightarrow | 0.03; \pm 0.05 ML \leftrightarrow | 0.1; \pm 1.1 ML \leftrightarrow |
| Cumulative 7 day | 1750 \pm 340 | 0.05; \pm 0.13 ML \leftrightarrow | 0.01; \pm 0.04 ML \leftrightarrow | -1.1; \pm 0.9 ML \leftrightarrow |
| Cumulative 14 day | 3510 \pm 530 | 0.02; \pm 0.11 ML \leftrightarrow | -0.05; \pm 0.05 ML \leftrightarrow | -1.7; \pm 0.9 ML \leftrightarrow |
| Cumulative 28 day | 7080 \pm 980 | 0.14; \pm 0.15 ML \leftrightarrow | -0.02; \pm 0.08 ML \leftrightarrow | -2.6; \pm 1.3 L \leftrightarrow |
| Smoothed 3 day | 250 \pm 60 | 0.04; \pm 0.15 ML \leftrightarrow | 0.00; \pm 0.05 ML \leftrightarrow | -0.7; \pm 1.0 ML \leftrightarrow |
| Smoothed 7 day | 260 \pm 40 | 0.09; \pm 0.12 ML \leftrightarrow | -0.02; \pm 0.05 ML \leftrightarrow | -1.1; \pm 0.9 ML \leftrightarrow |
| Smoothed 14 day | 260 \pm 30 | 0.10; \pm 0.13 ML \leftrightarrow | -0.04; \pm 0.06 ML \leftrightarrow | -2.0; \pm 0.9 ML \leftrightarrow |
| Smoothed 28 day | 260 \pm 30 | 0.09; \pm 0.19 ML \leftrightarrow | 0.01; \pm 0.13 ML \leftrightarrow | -3.3; \pm 1.6 P \leftrightarrow |
| Acute:Chronic ratio | 1.0 \pm 0.19 | -0.06; \pm 0.15 ML \leftrightarrow | 0.00; \pm 0.04 ML \leftrightarrow | 1.0; \pm 0.9 ML \leftrightarrow |
| Monotony | 0.82 \pm 0.20 | -0.04; \pm 0.15 ML \leftrightarrow | -0.04; \pm 0.08 ML \leftrightarrow | -1.8; \pm 1.2 ML \leftrightarrow |
| Strain | 1430 \pm 430 | 0.01; \pm 0.13 ML \leftrightarrow | -0.02; \pm 0.07 ML \leftrightarrow | -1.4; \pm 1.2 ML \leftrightarrow |

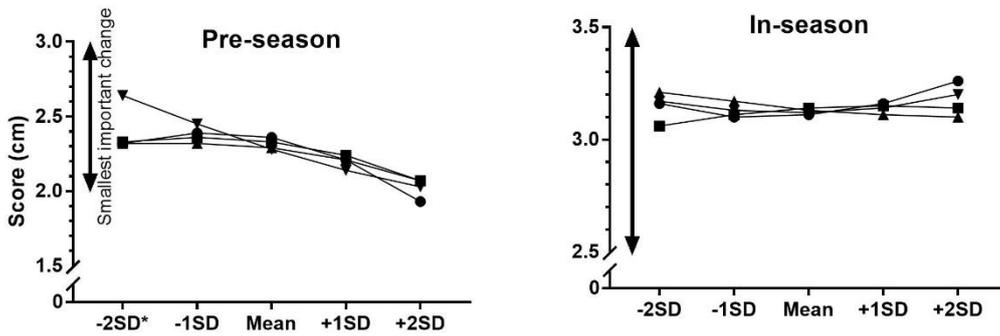
^aAll effects were trivial.

S&R, sit and reach test; DLT, dorsiflexion lunge test; AST, adductor squeeze test. SD, standard deviation; CL, confidence limits.

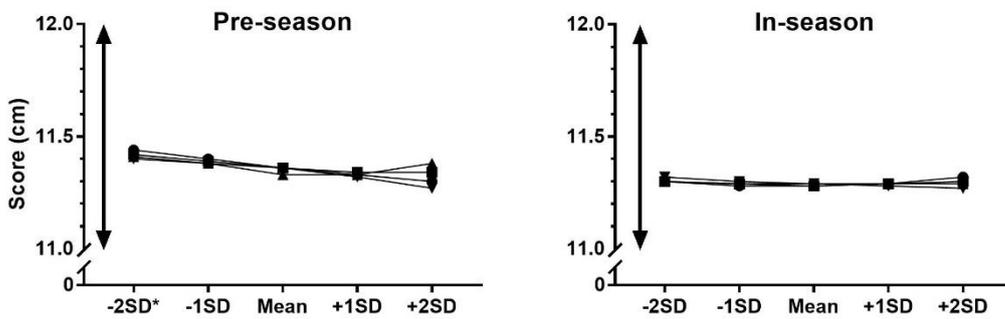
\leftrightarrow trivial; P, *possibly*; L, *likely*; VL, *very likely*; ML, *most likely*.

Cumulative, smoothed, and strain values are in arbitrary units.

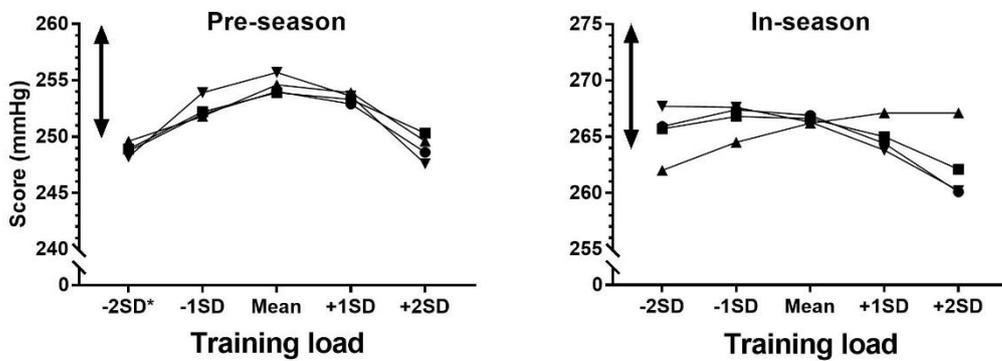
Sit and Reach Test



Dorsiflexion Lunge Test



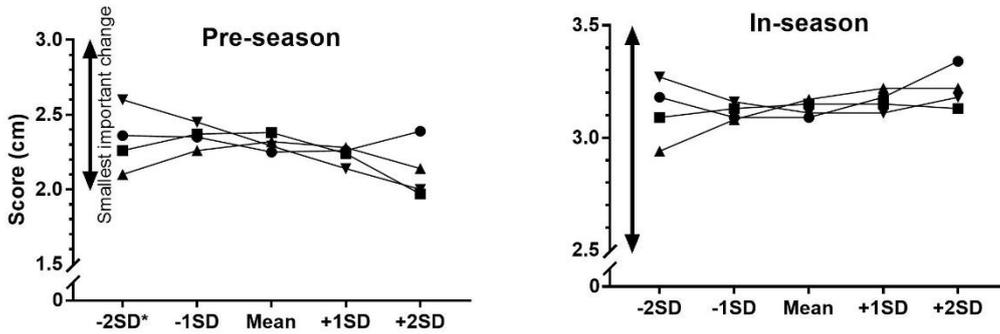
Adductor Squeeze Test



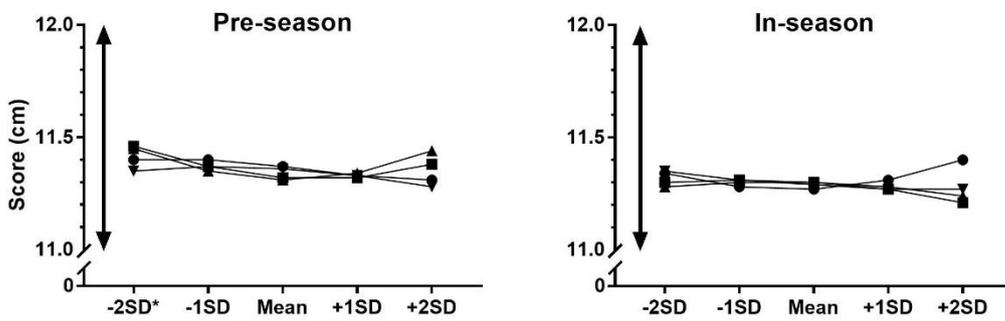
● Cumulative 7 day ■ Smoothed 3 day ▲ Acute:Chronic ratio ▼ Strain

Figure 4.1 Changes in screening scores with changes in training load (cumulative 7 day, smoothed 3 day, acute:chronic ratio, strain). *The estimates for the screening scores were calculated for zero training load where -2SD of training load was a negative value.

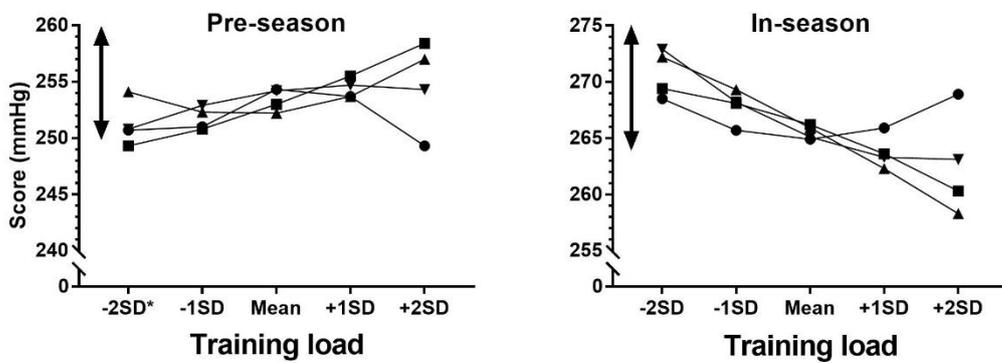
Sit and Reach Test



Dorsiflexion Lunge Test



Adductor Squeeze Test



● Cumulative 3 day ■ Cumulative 14 day ▲ Cumulative 28 day ▼ Monotony

Figure 4.2 Changes in screening scores with changes in training load (cumulative 3 day, cumulative 14 day, cumulative 28 day, monotony). *The estimates for the screening scores were calculated for zero training load where -2SD of training load was a negative value.

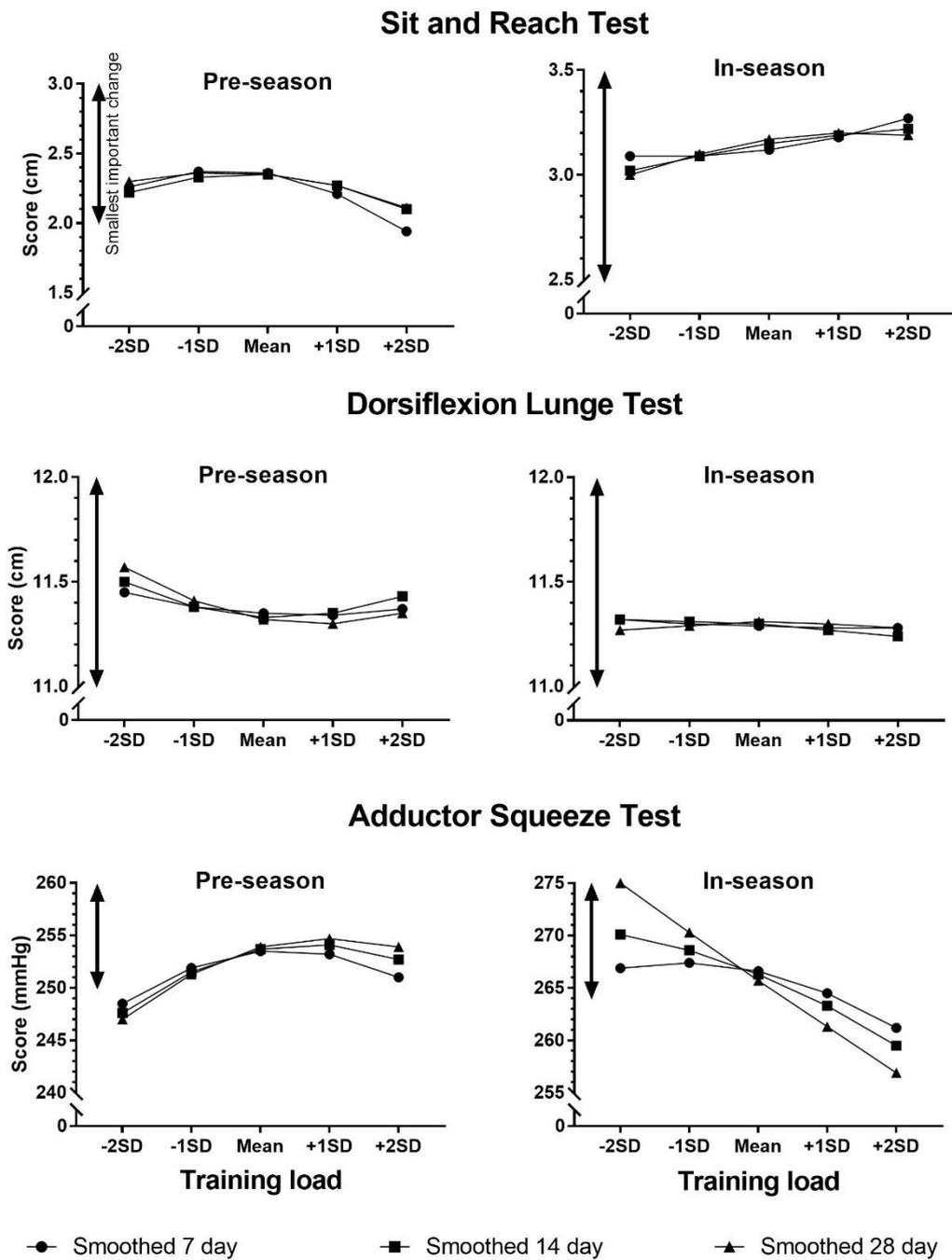


Figure 4.3 Changes in screening scores with changes in training load (smoothed 7 day, smoothed 14 day, smoothed 28 day).

4.4 Discussion

There were substantial small to moderate amounts of normal variability with some individual differences in variability associated with the weekly musculoskeletal screening tests. The tests which were conducted two or three days post-match (or main training session during pre-season) were not sensitive to changes in internal training load and may not provide an accurate indication of the athletes' readiness for training when used as measures of recovery.

4.4.1 Normal variability

This study is the first to have tracked weekly test scores throughout an entire season. The intra-tester reliability of the tests in the current study as quantified using ICC, were similar to those in studies with test-retest gaps of between 30 minutes and one week (Bennell et al., 1998; Gabbe et al., 2004; Malliaras et al., 2009). The normal variability of the test scores was approximately ± 1.0 cm for the S&R, ± 0.5 cm for the DLT, and $\pm 8\%$ for the AST. These values are similar to the previously reported SEMs (Bennell et al., 1998; Gabbe et al., 2004; Malliaras et al., 2009) and do not seem to be affected by regular exposure to training and competition throughout the season. Such stability in reliability despite physical challenges of a long competitive season indicate that substantial changes in weekly scores cannot be simply attributed to training-induced altered reliability of the tests. Various sources such as technique variation, equipment error, and true change in athletes' test performance contribute to the week-to-week changes in screening scores (Hopkins, 2000). The true change in test performance itself may arise from adaptation or maladaptation to training and competition, the residual effects or complete resolution of a previous injury, or minor incidents that affect

the test scores without limiting the athletes' capacity to fully participate in training (e.g. minor muscle contusions). Thus, it is important for clinicians to interpret the findings of weekly screening in light of possible contributing factors towards the change in the scores.

The typical error (noise) obscures the important change (signal) in any measure (Hopkins, 2000). In the concept of weekly screening, noise is represented by the normal variability of the scores as measured in the current study. The signal can be considered as the smallest change in the screening score that is associated with a substantial increase in the risk of injury. Reductions of approximately 12% and 6% in the hip adductors' strength of elite junior Australian footballers (as measured by a hand-held dynamometer) were reported during the week of groin injury onset and the preceding week, respectively, which represent the signal for that particular test (Crow et al., 2010). No studies to date have evaluated the signal for either of the tests for which the current study established the noise. Future studies investigating the signal should take into account the normal variability of the test scores throughout the season when interpreting the findings and assessing the potential of weekly screening tests for injury prevention purposes.

4.4.2 Individual differences in variability

Training, like any intervention, interacts with the athletes' individual characteristics making the effects more or less beneficial, harmful, or ineffective in different individuals (Hopkins, 2015). In the case of weekly screening, such interactions led to the observed individual differences in variability, which were substantial for the S&R and AST (Table 4.2). For instance, the S&R score in

players with typically low normal variability (1 SD below the mean) varied by approximately ± 0.5 cm from one week to another week, while players with typically high normal variability (1 SD above the mean) showed a typical week-to-week variation of approximately ± 1.5 cm. Applying an arbitrary threshold to the change in screening scores for flagging purposes may prove overly sensitive for some players and not sensitive enough for others.

A survey of athlete monitoring practices in high performance sports revealed that majority of coaching and support staff rely on visual identification of trends in the athletes' data to identify the ones who may benefit from an adjustment to training load (Taylor et al., 2012). Another common method was the use of red flags with thresholds being set by either arbitrary cut-off points or within-subject SDs (Taylor et al., 2012). On the basis of the observed individual differences in the current study and previous recommendations on the development of decision support systems (Robertson et al., 2017), the use of within-subject SDs in setting the flagging thresholds for weekly musculoskeletal screening is encouraged. In the absence of enough longitudinal data when within-subject SDs cannot be reliably estimated, practitioners may use the reported normal variations to detect abnormal changes in the screening scores. Practitioners can select a smallest detectable change of 1.5-2.8 times the error of measurement presented in this study.

4.4.3 Effects of training load

The observed trivial effects of training load on the test scores indicate that these tests are not sensitive to changes in internal training load when performed two or three days post-match or post-training. Subsequently, the screening scores

should be interpreted cautiously when used as measures of recovery. This finding is supported by the observed trivial differences between the test scores obtained at two versus three days post-match in the current study as well as the previously reported timeline of change in the measures of flexibility and peak force post-match (Dawson et al., 2005; Johnston et al., 2013; McLellan, Lovell, & Gass, 2011; Roe et al., 2016; Wollin, Thorborg, & Pizzari, 2017). The S&R score declines on day one post-match and returns to baseline on day two in elite Australian footballers (Dawson et al., 2005). Measures of lower limb strength return back to baseline by day one post-match (McLellan et al., 2011; Wollin et al., 2017) or do not change in the first place in team sport athletes (Johnston et al., 2013; Roe et al., 2016).

Training load has an established association with the recovery of athletes and injury risk (Gabbett, 2016). In the absence of a substantial relationship between training load and screening scores, a normal test score does not necessarily mean that the athlete is sufficiently recovered to process another training stimulus, and other more sensitive measures of recovery should be evaluated by practitioners. On the other hand, an abnormal screening score is often indicative of an underlying issue that needs to be investigated by the medical staff prior to the training session. There are also other benefits associated with musculoskeletal screening, which include identifying undiagnosed injuries or complaints, assessing the rehabilitation progression of previous injuries, establishing future return-to-play outcome measures for healthy athletes, and establishing rapport between the medical staff and athletes (Bahr, 2016; Bakken et al., 2016; Clarsen & Berge, 2016).

Overall, while weekly musculoskeletal screening appears to be a valuable athlete monitoring tool, clinicians need to be aware of the normal variability of the test scores and the individual differences in such variability when interpreting changes in screening scores. The lack of sensitivity of the investigated tests to training load should prompt clinicians to investigate the reasons behind substantial reductions in screening scores rather than casually attributing them to a match or training session that occurred more than two days prior to the screening.

A limitation of this study is that the current findings in regards to the effects of training load on the musculoskeletal screening scores are based on the sRPE derived internal measures of training load (measures of external training load were not available at the time of conducting this study) and may not necessarily apply to the external measures of training load (e.g. running distance). Considering the differences between adaptation pathways to physiological and biomechanical loads (Vanrenterghem et al., 2017), future studies need to investigate the relationship between external measures of training load and the response of the musculoskeletal system. In the current study, the screening results on a given day did not generally change the injury status of players on the day of screening. However, as a general limitation of working with elite athletes, the implemented interventions in response to the screening scores (e.g. additional treatment sessions) could have affected the screening scores in the following week. It should also be noted that the current study was conducted with elite male Australian footballers, and generalization of findings to females as well as athletes of other sports and levels of play should be done with caution. While fractional polynomial approach could have been used instead of the currently

used quadratic modelling, the use of this approach would have likely resulted in the same findings considering the clearly trivial effects of training load on changes in the screening scores.

4.5 Conclusion

A change in the screening scores larger than the identified normal variability is required to be considered a true change and the flagging systems applied to the screening scores need to account for the individual differences in variability. The studied tests are not sensitive to changes in training load as the scores return back to baseline by day two post-match or post-training when the screening is normally conducted.

Chapter 5 – Study 3: The individual and combined effects of multiple factors on the risk of soft tissue non-contact injuries in elite team sport athletes

Published:

Esmaeili, A., Hopkins, W. G., Stewart, A. M., Elias, G. P., Lazarus, B. H., & Aughey, R. J. (2018). The individual and combined effects of multiple factors on the risk of soft tissue non-contact injuries in elite team sport athletes. *Frontiers in Physiology*, 9(1280). doi: 10.3389/fphys.2018.01280

5.1 Introduction

Injuries can negatively affect team performance and impose substantial costs to sports clubs (Hagglund et al., 2013). Quantification of injury risk factors through athlete monitoring is now common practice in elite sports settings for the main purpose of injury prevention (Akenhead & Nassis, 2016; Taylor et al., 2012). These practices include monitoring individual training loads as well as the athletes' response to training through measures such as regular musculoskeletal screening and subjective wellness (Colby, Dawson, Peeling, et al., 2017; Morgan et al., 2014). Non-modifiable injury risk factors such as professional experience and history of previous injuries also affect training prescription and load modification practices (Blanch & Gabbett, 2016; Rogalski et al., 2013). Previous studies have investigated the effects of these injury risk factors predominantly in

isolation; however, injury is a multifactorial process and is influenced by multiple predisposing factors as well as an inciting event (Meeuwisse, 1994a). The primary aim of this study was therefore to evaluate the individual and combined effects of multiple factors on the risk of soft tissue non-contact injuries, and possible confounding effects between the risk factors.

Rolling averages have been a popular method of deriving absolute (e.g., 4-week cumulative load) and relative (e.g., acute-to-chronic workload ratio) measures of training load over various time periods (Drew & Finch, 2016). This approach has recently been criticized for overlooking the training load pattern, and disregarding the physiological principle that the effects of a training stimulus decline over time (Menaspa, 2017a). Exponentially weighted moving averages have been proposed as a better alternative to rolling averages (Menaspa, 2017h; Williams, West, et al., 2017); however, little evidence exists in support of the application of exponentially weighted moving averages in evaluating the risk of injuries (Drew et al., 2017; Sampson et al., 2017). The secondary aim of this study was to compare the effects of training load measures derived using rolling averages and exponentially weighted moving averages on the risk of injuries.

High acute-to-chronic workload ratios (ACWR) have consistently been associated with increased risk of injuries (Hulin, Gabbett, Lawson, et al., 2016; Murray, Gabbett, Townshend, & Blanch, 2017; Stares et al., 2018). High acute load and previous injuries are also established injury risk factors (Hulin, Gabbett, Lawson, et al., 2016; Rogalski et al., 2013; Toohey et al., 2017). These variables can both contribute to a high ACWR through an increased value of the numerator and a decreased value of the denominator used in calculation of ACWR,

respectively. It has been speculated that training and injury history may affect the relationship between ACWR and injury risk (Blanch & Gabbett, 2016); however, no studies to date have quantified such interactions. A further aim of this study was therefore to evaluate the extent to which the effects of high ACWR are explained by acute load and previous injuries in order to further the understanding of researchers and practitioners of the application of ACWR for injury prevention purposes.

5.2 Methods

5.2.1 Participants

All the fifty-five elite male players who were enlisted in an Australian football club over a period of two consecutive seasons participated in this study (45 in the first season and 44 in the second; mean age \pm SD; 22.9 ± 3.9 years). The study was approved by Victoria University Human Research Ethics Committee, and all participants provided written informed consent in accordance with the Declaration of Helsinki.

5.2.2 Seasonal structure

Pre-season training phase started in November and continued until late March of the following year. The main focus of the pre-season training program was to develop the physical capacity, technical, and tactical skills of players in preparation for the in-season phase. The in-season phase lasted from April to early September when the primary focus was on the weekend match performance as well as recovery and preparation for the next match throughout the week.

5.2.3 Injury definition and recording process

An injury was defined as any training or match related incident that resulted in a missed match during the in-season phase or ≥ 6 days of modified training during the pre-season phase (Colby, Dawson, Heasman, et al., 2017). Injuries were diagnosed and recorded by the club's head physiotherapist. The dates of injury onset and return to full training were recorded along with the injury mechanism and site. Only soft-tissue (muscle, tendon, and ligament) non-contact injuries of the lower limbs were considered for the analysis as these injuries are more likely to be preventable and influenced by the investigated variables (Gabbett, 2010). It should be noted that injury dates were assigned to sessions that made the final contribution to the injury occurrence in order to eliminate possible inconsistencies caused by delayed onset of symptoms. For example, when symptoms were reported the day after a match, the injury date was recorded as the match date.

5.2.4 History of previous injuries

History of previous injuries for individual players was quantified by creating two variables on each day using the injury records of the study period as well as the season prior to the commencement of the study for existing and drafted players (same injury definition and recording process as previous part). These variables were the number of days since return to full training from any previous injuries (contact and non-contact) and from a previous leg injury (contact and non-contact) in order to account for the decaying effects of previous injuries. These variables were reset to zero upon sustaining a relevant new injury and started counting up from one on the first day of return to full training.

5.2.5 Training load constructs and derived measures

Internal training load was quantified using the session rating of perceived exertion method (sRPE) for all training sessions and matches (RPE multiplied by the session duration) (Foster, 1998). External training load was monitored using global positioning system (GPS)/accelerometer units for field training sessions and matches (Optimeye S5, Catapult Innovations, Australia). Player Load™, total distance covered, and high-intensity running (HIR) distance ($>4.17 \text{ m}\cdot\text{s}^{-1}$) were extracted with the software (Sprint v5.1.3, Catapult Innovations, Australia) (Aughey, 2010; Boyd et al., 2013). These four internal and external training load constructs, which are commonly monitored in team sports, were then used to calculate several absolute and relative derived measures of training load over various time periods (Drew & Finch, 2016; Williams, Trewartha, et al., 2017).

Cumulative loads on each day were calculated as 7, 14, 21, and 28 day rolling averages as well as 7, 14, and 28 day smoothed loads. The smoothed load is an exponentially weighted moving average of training load, which accounts for the decaying effects of training using a decay factor λ (lambda) (Hunter, 1986; Williams, West, et al., 2017). The smoothed load at the end of each day is calculated as $[\lambda \times (\text{today's training load})] + [(1 - \lambda) \times \text{the smoothed load at the end of yesterday}]$. The decay factor λ defines a time constant $1/\lambda$ representing the period that contains approximately 2/3 of the total weighting in calculation of the smoothed load (Chapter 4). Decay factors of 0.14, 0.07, and 0.036 were used to calculate the smoothed loads representing time constants of 7, 14, and 28 days, respectively. The method of labelling the time constants used in the current study (time period = $1/\lambda$) is slightly different to the one recently suggested [$\lambda =$

$2/(\text{time period} + 1) \Rightarrow \text{time period} = (2 - \lambda)/\lambda$ (Williams, West, et al., 2017). Using the current method of labelling the time constant, the smoothed load of a given period has the highest correlation with the simple cumulative load of a similar period (Chapter 4). The first smoothed load at the beginning of each season was calculated by assigning the first daily load observation to the accumulated smoothed load on the first day of training (Murray, Gabbett, Townshend, & Blanch, 2017). Calculation of rolling averages, monotony, and strain at the beginning of each season started only after enough historical data were collected for each measure (e.g., seven days from the date of first training session for individual players for the 7-d rolling average).

Rolling average ACWR on each day was calculated as the 7-d rolling average load divided by the 28-d rolling average load (the coupled approach) (Hulin, Gabbett, Lawson, et al., 2016; Windt & Gabbett, 2018). Similarly, smoothed ACWR on each day was calculated as the 7-d smoothed load divided by the 28-d smoothed load (Murray, Gabbett, Townshend, & Blanch, 2017). Training monotony on each day was quantified as the 7-d rolling average training load divided by the standard deviation of daily loads of the past seven days (Foster, 1998). Training strain was determined by multiplying the sum of daily loads of the past seven days into the training monotony (Foster, 1998). The daily load of the current day was included in calculation of the derived measures of training load on each day as the data were later analysed on a daily basis.

5.2.6 Professional experience

Professional experience was defined as the number of years spent in the Australian football league (AFL) system at the end of each season and was

categorized in three groups of development (1–2 years), main group (3–6 years), and veterans (7+ years) (Stares et al., 2018).

5.2.7 Musculoskeletal screening

Regular musculoskeletal screening (as opposed to pre-season screening) was conducted once a week prior to the first field training session of the week, which was planned two or three days after a match (in-season) or a main training session (pre-season) (Chapter 4). The screening tests (one attempt) were left and right dorsiflexion lunge test (for calf flexibility/ankle range of motion), sit-and-reach test (for lower back/hamstring flexibility), and adductor squeeze test (for hip adductors' strength) at three angles of hip flexion (0°, 45°, and 90°). The details description of the tests were as follows:

Sit-and-reach test- Players placed their bare feet against the sit and reach box and their middle fingers on top of each other. They were then asked to stretch forward as far as possible and hold the position for one second while keeping the knees straight. The reach distance from the tip of the middle fingers relative to the toe line was recorded (Gabbe et al., 2004).

Dorsiflexion lunge test- A permanent tape measure was fixed on the floor with 0 cm mark at a wall junction. Players were asked to place the big toe and heel of the testing leg beside the tape. They were then instructed to lunge forward until the knee touches the wall while keeping the heel in contact with the floor. The maximum distance from the tip of the big toe to the wall was recorded (Bennell et al., 1998).

Adductor squeeze test- With players in a supine position, a sphygmomanometer cuff pre-inflated to 20 mmHg was placed between the knees. Players were asked to maximally squeeze the cuff and hold for one second and the maximum pressure displayed on the dial was recorded. The test was conducted in three hip flexion angles of 0°, 45°, and 90° (Malliaras et al., 2009).

5.2.8 Subjective wellness

Subjective wellness was assessed using a short computer based questionnaire, which has previously been developed based on the areas of interest of sports science and conditioning staff as well as the frequently used items in the athlete monitoring literature (Gastin, Meyer, et al., 2013). The questionnaire was completed prior to training sessions and the items included fatigue, sleep quality, general muscle soreness, mood, and stress. Each item was rated on a scale of one (feeling as bad as possible) to ten (feeling as good as possible).

5.2.9 Statistical analysis

All analyses were performed with the Statistical Analysis System (version 9.4, SAS Institute, Cary, NC). A small proportion (<6%) of daily training load observations for GPS-derived constructs (total distance and high-intensity running distance) was missing, owing to poor GPS reception. Player Load (accelerometer-derived construct) was still recorded for these sessions and was used to impute the missing GPS data with a general linear mixed model (Proc Mixed). Player Load and session duration (time on the field for matches) were the fixed effects, while player identity and date were the random effects. Separate imputations were performed for matches and training sessions.

The generalized linear mixed model (Proc Glimmix) with the complementary log-log link function was used to investigate the individual, combined, and possible confounding effects of factors affecting the risk (hazard) of lower limb soft-tissue non-contact injuries. Non-training days for individual players (daily sRPE=0) as well as the days when a player was recovering from any previous injury were removed from the analyses after contributing to calculation of the derived measures of training load. The analyses were performed in three parts.

The individual effects of each potential risk factor were investigated in the first part. The effects of training load were evaluated by splitting the derived training load measures of each phase (pre-season and in-season) in each season into four quantiles (groups with nearly equal number of observations) for each player separately (individualised thresholds) (Bartlett, O'Connor, Pitchford, Torres-Ronda, & Robertson, 2017; Hulin, Gabbett, Lawson, et al., 2016). The thresholds were not individualised for relative (rolling average ACWR and smoothed ACWR) and purely distribution-based measures (monotony), as they are calculated as ratios. This approach of devising the load levels was taken to account for differences between seasons, between season phases, and between individual players. The training load levels were subjectively labelled as low, moderate-low, moderate-high, and high. Soft tissue non-contact injuries were assigned to the four levels according to their associated derived training load measure on the day of injury. No latent period was included, as the derived measures were updated and analysed daily. Injury hazard (risk per player per exposure day) for each load level was estimated in a model where training load, season, and season phase were the fixed effects and player identity was the random effect. Within player

changes between seasons were also specified with a random effect (interaction of player identity and season), but this term had zero variance. An overdispersion factor was included in the model to allow for the proportion of injuries on any given day to be not perfectly binomially distributed. The low training load level was selected as the reference group in order to calculate the hazard ratio for each level representing the effect of training load on the risk of injuries (Hopkins et al., 2007). The only exceptions were rolling average ACWR and smoothed ACWR measures, where the moderate-high level was selected as the reference group based on previous findings (Hulin, Gabbett, Caputi, et al., 2016; Malone et al., 2017).

The individual effects of history of any previous injuries and previous leg injuries were similarly evaluated by splitting the pool of the associated variables into four quantiles. The quantile representing the longest period since a previous relevant injury was taken as the reference group. The effects of professional experience were quantified by estimating the injury hazard for the three experience groups with the main group (3–6 years) selected as the reference in calculation of hazard ratios.

Musculoskeletal screening and wellness scores were converted into z-scores (scores with a mean of 0 and SD of 1) for each individual in each season and season phase separately. The injury status of a given player on each exposure day was associated with the latest available score, typically 0–6 days previously for musculoskeletal screening and 0–2 days previously for wellness. The injury hazards associated with z-scores ≤ -1 and ≤ -1.5 (representing more than 1 within-subject SD and 1.5 within-subject SD reduction in those variables) were

compared to the injury hazards of the reference groups (z-scores >-1 and >-1.5 , respectively). The resultant hazard ratios represented the effects of substantial reductions in musculoskeletal screening and wellness scores on the risk of injuries.

In the second part, the effects of training load were evaluated after adjusting for previous leg injuries by including history of previous leg injuries, training load, season, and season phase as the fixed effects and player identity as the random effect. History of previous leg injuries was chosen over the history of any previous injuries as it showed a larger effect in the first part of the analysis. The combined effects of high training load and a recent leg injury (the level representing the shortest time since a previous leg injury) were also estimated in the model with the combination of low training load (moderate-high for ACWR variables) and the level representing the longest time since a previous leg injury taken as the reference. The random effect (player identity) was estimated as a standard deviation in log units to evaluate individual differences in injury risk. The standard deviation was doubled to interpret its magnitude (Smith & Hopkins, 2011), representing the difference between injury-prone (1 SD above the mean) and robust (1 SD below the mean) players after accounting for training load and previous leg injuries. After back-transformation, this difference was expressed as a hazard ratio.

In the third part, variables that showed substantial associations with the risk of injuries in part one of the analysis (professional experience, sit-and-reach test, adductor squeeze tests, mood, but not general muscle soreness) were re-evaluated after adjusting for training load and previous leg injuries in models

similar to those in part two of the analysis. Smoothed 7-d Player Load was taken as the representative measure of training load, since the variables of interest were speculatively more likely to be influenced by acute load. The reference levels for the adjusted effects of these variables were as explained in part one. The effects of each of these variables were also quantified by estimating the combination of the highest risk level of each of the selected variables with high acute load and a history of a recent leg injury relative to the reference groups. Two reference groups were defined. The first reference group (lowest risk scenario) was the combination of low training load, long time since a previous leg injury, and the lowest risk level identified in part one for the selected variables. The second reference group (regular scenario) was the combination of all levels excluding the highest risk level for each of the variables. The effects of rolling average ACWR and smoothed ACWR were similarly evaluated after adjusting for the associated acute load (7-d rolling average load for rolling average ACWR and 7-d smoothed load for smoothed ACWR) and previous leg injuries.

The thresholds for the smallest important hazard ratio representing increase and decrease in injury risk were 1.11 and 0.90, respectively (Hopkins, 2010). The uncertainty in all effects was expressed as 90% confidence limits, and qualitatively as chances that the true value of the effect was substantial for clear effects using the following scale: <0.5%, *most unlikely*; 0.5% to <5%, *very unlikely*; 5% to <25%, *unlikely*; 25% to <75%, *possibly*; 75% to <95%, *likely*; 95% to <99.5%, *very likely*; >99.5%, *most likely*. The effect was deemed unclear when both the lower confidence limit was <0.90 and the upper confidence limit was

>1.11 (Hopkins et al., 2009). Results were rounded and reported to two significant digits (Hopkins, Batterham, Pyne, & Impellizzeri, 2011).

5.3 Results

Sixty-five lower limb soft tissue non-contact injuries were sustained by 33 individual athletes over the study period (first season=28, second season=37; pre-season=26, in-season=39). Mean thresholds for the four levels of derived training load measures over pre-season and in-season are summarized in Table 5.1. Thresholds for each level were higher during pre-season compared to the in-season.

Table 5.1. Daily mean thresholds of training load levels (quantiles) for pre-season and in-season.

| Derived measure | Level | sRPE (AU) | | Player Load (AU) | | Total distance (m) | | High-intensity running distance (m) | |
|----------------------|---------------|------------|-----------|------------------|-----------|--------------------|-----------|-------------------------------------|-----------|
| | | Pre-season | In-season | Pre-season | In-season | Pre-season | In-season | Pre-season | In-season |
| 7-d rolling average | High | >450 | >300 | >350 | >310 | >3700 | >3300 | >1100 | >800 |
| | Moderate-high | 350-450 | 270-300 | 280-350 | 260-310 | 3000-3700 | 2800-3300 | 820-1100 | 650-800 |
| | Moderate-low | 260-349 | 240-269 | 200-279 | 200-259 | 2100-2999 | 2200-2799 | 510-819 | 480-649 |
| 14-d rolling average | High | >420 | >290 | >330 | >300 | >3500 | >3100 | >1000 | >760 |
| | Moderate-high | 350-420 | 270-290 | 280-330 | 250-300 | 2900-3500 | 2700-3100 | 800-1000 | 630-760 |
| | Moderate-low | 260-349 | 240-269 | 210-279 | 210-249 | 2100-2899 | 2200-2699 | 560-799 | 500-629 |
| 21-d rolling average | High | >400 | >280 | >310 | >290 | >3300 | >3000 | >930 | >730 |
| | Moderate-high | 330-400 | 260-280 | 260-310 | 250-290 | 2800-3300 | 2600-3000 | 760-930 | 620-730 |
| | Moderate-low | 260-329 | 250-259 | 190-259 | 210-249 | 2000-2799 | 2200-2599 | 540-759 | 510-619 |
| 28-d rolling average | High | >380 | >280 | >300 | >280 | >3200 | >2900 | >880 | >720 |
| | Moderate-high | 310-380 | 260-280 | 250-300 | 250-280 | 2700-3200 | 2600-2900 | 740-880 | 620-720 |
| | Moderate-low | 250-309 | 250-259 | 190-249 | 210-249 | 2000-2699 | 2200-2599 | 560-739 | 520-619 |
| 7-d smoothed | High | >460 | >300 | >340 | >300 | >3600 | >3200 | >1100 | >770 |
| | Moderate-high | 380-460 | 270-300 | 280-340 | 250-300 | 3000-3600 | 2600-3200 | 830-1100 | 620-770 |
| | Moderate-low | 290-379 | 240-269 | 200-279 | 200-249 | 2100-2999 | 2200-2599 | 560-829 | 490-619 |
| 14-d smoothed | High | >450 | >290 | >320 | >280 | >3400 | >3000 | >1000 | >720 |
| | Moderate-high | 360-450 | 270-290 | 260-320 | 250-280 | 2800-3400 | 2600-3000 | 790-1000 | 620-720 |
| | Moderate-low | 290-359 | 250-269 | 200-259 | 210-249 | 2100-2799 | 2300-2599 | 570-789 | 530-619 |
| 28-d smoothed | High | >460 | >280 | >310 | >270 | >3300 | >2800 | >1000 | >690 |
| | Moderate-high | 360-460 | 270-280 | 250-310 | 250-270 | 2600-3300 | 2600-2800 | 770-1000 | 620-690 |
| | Moderate-low | 310-359 | 250-269 | 190-249 | 220-249 | 2000-2599 | 2300-2599 | 590-769 | 550-619 |
| | Low | <310 | <250 | <190 | <220 | <2000 | <2300 | <590 | <550 |

| | | | | | | | | | |
|----------------------|---------------|-----------|-----------|-----------|-----------|-------------|-------------|-----------|-----------|
| Rolling average ACWR | High | >1.25 | >1.14 | >1.53 | >1.22 | >1.52 | >1.22 | >1.50 | >1.24 |
| | Moderate-high | 1.01-1.25 | 1.03-1.14 | 1.10-1.53 | 1.05-1.22 | 1.10-1.52 | 1.05-1.22 | 1.06-1.50 | 1.03-1.24 |
| | Moderate-low | 0.82-1.00 | 0.92-1.02 | 0.86-1.09 | 0.87-1.04 | 0.85-1.09 | 0.88-1.04 | 0.78-1.05 | 0.83-1.02 |
| | Low | <0.82 | <0.92 | <0.86 | <0.87 | <0.85 | <0.88 | <0.78 | <0.83 |
| Smoothed ACWR | High | >1.11 | >1.10 | >1.49 | >1.16 | >1.48 | >1.16 | >1.43 | >1.16 |
| | Moderate-high | 0.97-1.11 | 1.01-1.10 | 1.16-1.49 | 1.02-1.16 | 1.15-1.48 | 1.02-1.16 | 1.09-1.43 | 1.00-1.16 |
| | Moderate-low | 0.86-0.96 | 0.92-1.00 | 0.92-1.15 | 0.89-1.01 | 0.91-1.14 | 0.89-1.01 | 0.86-1.08 | 0.84-0.99 |
| | Low | <0.86 | <0.92 | <0.92 | <0.89 | <0.91 | <0.89 | <0.86 | <0.84 |
| Monotony | High | >1.11 | >0.87 | >0.79 | >0.74 | >0.79 | >0.75 | >0.76 | >0.70 |
| | Moderate-high | 0.95-1.11 | 0.78-0.87 | 0.73-0.79 | 0.66-0.74 | 0.73-0.79 | 0.67-0.75 | 0.66-0.76 | 0.61-0.70 |
| | Moderate-low | 0.80-0.94 | 0.71-0.77 | 0.59-0.72 | 0.58-0.65 | 0.59-0.72 | 0.58-0.66 | 0.57-0.65 | 0.54-0.60 |
| | Low | <0.80 | <0.71 | <0.59 | <0.58 | <0.59 | <0.58 | <0.57 | <0.54 |
| Strain | High | >3400 | >1800 | >1900 | >1600 | >20000 | >17000 | >5500 | >3800 |
| | Moderate-high | 2300-3400 | 1500-1800 | 1400-1900 | 1200-1600 | 15000-20000 | 13000-17000 | 3800-5500 | 2800-3800 |
| | Moderate-low | 1500-2299 | 1300-1499 | 930-1399 | 860-1199 | 9700-14999 | 9200-12999 | 2200-3799 | 1900-2799 |
| | Low | <1500 | <1300 | <930 | <860 | <9700 | <9200 | <2200 | <1900 |

sRPE, session rating of perceived exertion; AU, arbitrary units; ACWR, acute-to-chronic workload ratio.

5.3.1 The individual effects

The individual effects of training load are summarized in Table 5.2. High levels of cumulative measures (rolling averages and smoothed loads), rolling average and smoothed ACWR, monotony, and strain were typically associated with substantial increases in the risk of injuries. The effects were considerably larger for smoothed cumulative and relative measures compared to similar measures derived using rolling averages. High 14-d smoothed Player Load had the largest effect on the risk of injuries (hazard ratio 3.2, 90% confidence limits 1.86–5.4) compared to other measures of cumulative load. In general, the 14-d period was associated with larger increases in the risk of injuries compared to other periods for both high rolling average and high smoothed cumulative loads. High smoothed ACWR was associated with the largest absolute risk of injury (injury hazard 0.79) compared to all other training load measures. Moderate-high level of smoothed ACWR was generally associated with substantially lower risk of injuries compared to all other smoothed ACWR levels.

The individual effects of previous injuries and professional experience are summarized in Table 5.3. A recent history of injuries was associated with a higher risk of injuries when compared to the reference level. The effect was slightly larger for recent leg injuries compared to any recent injuries despite the “recent” level covering a longer period for leg injuries (<85 days) compared to any injuries (<53 days). Players with 7+ years of professional experience were at a higher risk of injuries compared to the reference level (3–6 years).

Table 5.2. Individual effects of training load on the risk of injuries derived from part one of the analysis.^a

| Derived measure | Level | sRPE | Player Load | Total distance | High-intensity running distance |
|----------------------|---------------|---|---|---|---|
| 7-d rolling average | High | 0.54%, 2.1 (1.29-3.5)^{***} | 0.50%, 1.34 (0.86-2.1) | 0.47%, 1.27 (0.81-2.0) | 0.45%, 1.49 (0.91-2.4)^{**} |
| | Moderate-high | 0.42%, 1.62 (0.96-2.7)^{**} | 0.28%, 0.75 (0.45-1.25) | 0.32%, 0.86 (0.53-1.41) | 0.39%, 1.28 (0.78-2.1) |
| | Moderate-low | 0.30%, 1.15 (0.66-2.0) | 0.36%, 0.97 (0.60-1.57) | 0.34%, 0.91 (0.56-1.47) | 0.36%, 1.19 (0.72-1.97) |
| | Low | 0.26%, Reference | 0.37%, Reference | 0.37%, Reference | 0.30%, Reference |
| 14-d rolling average | High | 0.70%, 2.1 (1.30-3.2)^{***} | 0.64%, 1.90 (1.21-3.0)^{***} | 0.67%, 1.84 (1.18-2.9)^{***} | 0.67%, 1.99 (1.27-3.1)^{***} |
| | Moderate-high | 0.36%, 1.06 (0.63-1.8) | 0.31%, 0.91 (0.54-1.55) | 0.29%, 0.80 (0.47-1.35) | 0.41%, 1.20 (0.73-1.97) |
| | Moderate-low | 0.19%, 0.55 (0.30-1.02)⁰⁰ | 0.28%, 0.83 (0.49-1.43) | 0.26%, 0.71 (0.42-1.23) | 0.17%, 0.49 (0.26-0.93)⁰⁰ |
| | Low | 0.34%, Reference | 0.34%, Reference | 0.36%, Reference | 0.34%, Reference |
| 21-d rolling average | High | 0.52%, 1.60 (1.02-2.5)^{**} | 0.42%, 1.15 (0.72-1.83) | 0.37%, 1.02 (0.63-1.65) | 0.55%, 1.50 (0.96-2.3)^{**} |
| | Moderate-high | 0.24%, 0.70 (0.41-1.22) | 0.43%, 1.19 (0.75-1.90) | 0.50%, 1.38 (0.89-2.2) | 0.33%, 0.92 (0.56-1.50) |
| | Moderate-low | 0.42%, 1.24 (0.78-1.99) | 0.33%, 0.91 (0.56-1.49) | 0.31%, 0.84 (0.51-1.39) | 0.31%, 0.84 (0.51-1.40) |
| | Low | 0.34%, Reference | 0.36%, Reference | 0.36%, Reference | 0.36%, Reference |
| 28-d rolling average | High | 0.44%, 1.14 (0.72-1.78) | 0.39%, 1.08 (0.68-1.74) | 0.36%, 1.08 (0.67-1.77) | 0.49%, 1.57 (0.98-2.5)^{**} |
| | Moderate-high | 0.28%, 0.74 (0.45-1.22) | 0.36%, 0.99 (0.61-1.59) | 0.36%, 1.07 (0.65-1.74) | 0.36%, 1.14 (0.69-1.88) |
| | Moderate-low | 0.35%, 0.90 (0.56-1.45) | 0.35%, 0.96 (0.60-1.55) | 0.39%, 1.17 (0.73-1.88) | 0.30%, 0.96 (0.57-1.62) |
| | Low | 0.38%, Reference | 0.36%, Reference | 0.34%, Reference | 0.31%, Reference |
| 7-d smoothed | High | 0.67%, 2.5 (1.53-4.0)^{****} | 0.70%, 2.8 (1.70-4.6)^{****} | 0.70%, 2.6 (1.58-4.1)^{****} | 0.70%, 2.6 (1.59-4.1)^{****} |
| | Moderate-high | 0.27%, 0.99 (0.56-1.74) | 0.30%, 1.17 (0.66-2.1) | 0.27%, 0.99 (0.56-1.75) | 0.25%, 0.91 (0.51-1.62) |
| | Moderate-low | 0.29%, 1.05 (0.60-1.83) | 0.27%, 1.06 (0.59-1.91) | 0.27%, 0.97 (0.55-1.72) | 0.29%, 1.05 (0.60-1.84) |
| | Low | 0.27%, Reference | 0.25%, Reference | 0.28%, Reference | 0.27%, Reference |
| 14-d smoothed | High | 0.56%, 2.2 (1.34-3.7)^{***} | 0.65%, 3.2 (1.86-5.4)^{****} | 0.63%, 3.1 (1.79-5.2)^{****} | 0.58%, 2.8 (1.65-4.9)^{****} |
| | Moderate-high | 0.43%, 1.71 (1.01-2.9)^{**} | 0.25%, 1.21 (0.65-2.3) | 0.29%, 1.43 (0.78-2.6) | 0.43%, 2.1 (1.19-3.7)^{***} |
| | Moderate-low | 0.27%, 1.06 (0.59-1.89) | 0.40%, 1.95 (1.10-3.4)^{**} | 0.38%, 1.84 (1.04-3.3)^{**} | 0.29%, 1.41 (0.77-2.6) |
| | Low | 0.25%, Reference | 0.21%, Reference | 0.21%, Reference | 0.21%, Reference |
| 28-d smoothed | High | 0.46%, 1.69 (1.03-2.8)^{**} | 0.49%, 2.7 (1.50-4.8)^{**} | 0.49%, 2.7 (1.49-4.8)^{**} | 0.58%, 2.8 (1.65-4.9)^{****} |
| | Moderate-high | 0.40%, 1.48 (0.89-2.5) | 0.45%, 2.5 (1.38-4.5)^{**} | 0.50%, 2.7 (1.53-4.9)^{**} | 0.34%, 1.65 (0.92-3.0)^{**} |
| | Moderate-low | 0.35%, 1.30 (0.77-2.2) | 0.38%, 2.1 (1.14-3.8)^{**} | 0.34%, 1.83 (0.99-3.4)^{**} | 0.38%, 1.84 (1.04-3.3)^{**} |
| | Low | 0.27%, Reference | 0.18%, Reference | 0.18%, Reference | 0.21%, Reference |

| | | | | | |
|----------------------|---------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| Rolling average ACWR | High | 0.58%, 2.1 (1.32-3.3)*** | 0.57%, 2.2 (1.36-3.6)*** | 0.56%, 2.4 (1.48-3.9)**** | 0.49%, 1.37 (0.88-2.1) |
| | Moderate-high | 0.28%, Reference | 0.26%, Reference | 0.23%, Reference | 0.36%, Reference |
| | Moderate-low | 0.29%, 1.05 (0.62-1.79) | 0.38%, 1.47 (0.88-2.5) | 0.44%, 1.85 (1.11-3.1)** | 0.33%, 0.90 (0.55-1.47) |
| | Low | 0.29%, 1.03 (0.61-1.75) | 0.22%, 0.84 (0.47-1.52) | 0.22%, 0.92 (0.51-1.67) | 0.24%, 0.67 (0.39-1.14) |
| Smoothed ACWR | High | 0.70%, 4.0 (2.4-6.7)**** | 0.79%, 6.8 (3.5-13)**** | 0.79%, 6.8 (3.6-13)**** | 0.75%, 4.6 (2.6-8.1)**** |
| | Moderate-high | 0.18%, Reference | 0.12%, Reference | 0.12%, Reference | 0.16%, Reference |
| | Moderate-low | 0.27%, 1.52 (0.83-2.8) | 0.22%, 1.92 (0.90-4.0)** | 0.25%, 2.1 (1.01-4.4)** | 0.34%, 2.0 (1.09-3.9)** |
| | Low | 0.31%, 1.75 (0.98-3.1)** | 0.38%, 3.3 (1.64-6.7)**** | 0.36%, 3.0 (1.52-6.3)*** | 0.26%, 1.59 (0.83-3.0) |
| Monotony | High | 0.52%, 1.53 (0.96-2.4)** | 0.54%, 1.98 (1.21-3.2)*** | 0.54%, 2.4 (1.44-4.1)*** | 0.62%, 2.0 (1.26-3.2)*** |
| | Moderate-high | 0.34%, 1.01 (0.61-1.67) | 0.33%, 1.21 (0.72-2.0) | 0.32%, 1.44 (0.82-2.5) | 0.26%, 0.86 (0.50-1.48) |
| | Moderate-low | 0.31%, 0.92 (0.54-1.54) | 0.34%, 1.23 (0.75-2.0) | 0.42%, 1.91 (1.16-3.2)*** | 0.32%, 1.05 (0.64-1.73) |
| | Low | 0.34%, Reference | 0.28%, Reference | 0.22%, Reference | 0.31%, Reference |
| Strain | High | 0.59%, 1.81 (1.15-2.9)*** | 0.54%, 1.89 (1.15-3.1)*** | 0.46%, 1.49 (0.91-2.5)** | 0.55%, 1.95 (1.20-3.2)*** |
| | Moderate-high | 0.35%, 1.06 (0.64-1.76) | 0.37%, 1.31 (0.78-2.2) | 0.42%, 1.37 (0.83-2.3) | 0.33%, 1.16 (0.68-1.98) |
| | Moderate-low | 0.25%, 0.76 (0.44-1.32) | 0.33%, 1.14 (0.66-1.96) | 0.32%, 1.05 (0.62-1.78) | 0.35%, 1.22 (0.72-2.1) |
| | Low | 0.33%, Reference | 0.29%, Reference | 0.31%, Reference | 0.29%, Reference |

^aValues are injury hazard (risk per player per exposure day), hazard ratio (with 90% confidence limits). Substantial effects are in bold.

Likelihood of increased risk of injuries: * *possibly*, ** *likely*, *** *very likely*, **** *most likely*.

Likelihood of decreased risk of injuries: ⁰⁰ *Likely*.

sRPE, session rating of perceived exertion; ACWR, acute-to-chronic workload ratio.

Table 5.3. Individual effects of history of previous injuries and professional experience on the risk of injuries derived from part one of the analysis.

| Variable | Level | Injury hazard, hazard ratio (90% confidence limits) |
|----------------------------------|--------------|---|
| History of any previous injuries | <53 days | 0.44%, 1.81 (0.97-3.4)** |
| | 53-154 days | 0.32%, 1.30 (0.67-2.5) |
| | 155-362 days | 0.39%, 1.61 (0.83-3.1) |
| | >362 days | 0.25%, Reference |
| History of previous leg injuries | <85 days | 0.52%, 2.1 (1.19-3.7)*** |
| | 85-232 days | 0.37%, 1.49 (0.81-2.7) |
| | 233-364 days | 0.42%, 1.68 (0.82-3.4) |
| | >364 days | 0.25%, Reference |
| Professional experience | 1-2 years | 0.38%, 1.26 (0.69-2.3) |
| | 3-6 years | 0.30%, Reference |
| | 7+ years | 0.55%, 1.85 (0.98-3.6)** |

Substantial effects are in bold.

Likelihood of increased risk of injuries: * *possibly*, ** *likely*, *** *very likely*, **** *most likely*.

The individual effects of weekly musculoskeletal screening and subjective wellness scores are summarized in Table 5.4. Substantial reductions in the sit-and-reach test and adductor squeeze tests (but not the dorsiflexion lunge tests) were associated with higher risk of injuries. The effects were larger when the threshold for a substantial reduction was set at 1.5 SD as opposed to 1 SD. Among the subjective wellness variables, only substantial reductions (worse scores) in mood were associated with an increased risk of injuries. Unexpectedly, worse scores for general muscle soreness were associated with a lower risk of injuries. The descriptive statistics for the subjective wellness items were as

follows: mean of the player means: 7.8 to 8.2; SD of the player means: 0.44 to 0.61; mean of the within-player SDs: 0.5 to 0.68. The descriptive statistics for the musculoskeletal screening tests were nearly identical to the values previously provided in detail (Chapter 4).

Table 5.4. Individual effects of musculoskeletal screening and subjective wellness scores on the risk of injuries derived from part one of the analysis.

| Musculoskeletal screening | | | Subjective wellness | | |
|-------------------------------|---------|---|-------------------------|---------|---|
| Screening test | Z-score | Injury hazard, hazard ratio (90% confidence limits) | Wellness item | Z-score | Injury hazard, hazard ratio (90% confidence limits) |
| Left dorsiflexion lunge test | < -1.5 | 0.13%, 0.56 (0.23-1.38) | Fatigue | < -1.5 | 0.33%, 0.87 (0.46-1.63) |
| | ≥ -1.5 | 0.24%, Reference | | ≥ -1.5 | 0.38%, Reference |
| | < -1 | 0.23%, 1.00 (0.59-1.69) | | < -1 | 0.28%, 0.71 (0.41-1.22) |
| | ≥ -1 | 0.23%, Reference | | ≥ -1 | 0.39%, Reference |
| Right dorsiflexion lunge test | < -1.5 | 0.20%, 0.86 (0.41-1.84) | Sleep quality | < -1.5 | 0.46%, 1.25 (0.70-2.2) |
| | ≥ -1.5 | 0.23%, Reference | | ≥ -1.5 | 0.37%, Reference |
| | < -1 | 0.13%, 0.54 (0.25-1.14) | | < -1 | 0.40%, 1.08 (0.67-1.76) |
| | ≥ -1 | 0.25%, Reference | | ≥ -1 | 0.37%, Reference |
| Sit-and-reach test | < -1.5 | 0.53%, 2.6 (1.56-4.4) **** | General muscle soreness | < -1.5 | 0.%, - Very low ^a |
| | ≥ -1.5 | 0.20%, Reference | | ≥ -1.5 | 0.%, Reference |
| | < -1 | 0.37%, 1.75 (1.11-2.8) ** | | < -1 | 0.12%, 0.28 (0.13-0.61) ⁰⁰⁰ |
| | ≥ -1 | 0.21%, Reference | | ≥ -1 | 0.42%, Reference |
| Adductor squeeze test 0° | < -1.5 | 0.45%, 2.1 (1.12-3.8) *** | Mood | < -1.5 | 0.68%, 1.92 (1.11-3.3) *** |
| | ≥ -1.5 | 0.22%, Reference | | ≥ -1.5 | 0.36%, Reference |
| | < -1 | 0.30%, 1.34 (0.86-2.1) | | < -1 | 0.53%, 1.51 (0.94-2.4) ** |
| | ≥ -1 | 0.22%, Reference | | ≥ -1 | 0.35%, Reference |
| Adductor squeeze test 45° | < -1.5 | 0.38%, 1.69 (0.93-3.1) ** | Stress | < -1.5 | 0.55%, 1.53 (0.85-2.8) |
| | ≥ -1.5 | 0.22%, Reference | | ≥ -1.5 | 0.36%, Reference |
| | < -1 | 0.25%, 1.06 (0.65-1.73) | | < -1 | 0.48%, 1.33 (0.81-2.2) |
| | ≥ -1 | 0.23%, Reference | | ≥ -1 | 0.36%, Reference |
| Adductor squeeze test 90° | < -1.5 | 0.54%, 2.9 (1.80-4.7) **** | | | |
| | ≥ -1.5 | 0.19%, Reference | | | |
| | < -1 | 0.38%, 2.1 (1.44-3.2) **** | | | |
| | ≥ -1 | 0.18%, Reference | | | |

^aAll injuries were sustained in the reference group.

Substantial effects are in bold.

Likelihood of increased risk of injuries: * possibly, ** likely, *** very likely, **** most likely.

Likelihood of decreased risk of injuries: ⁰⁰⁰ very likely.

5.3.2 The adjusted and combined effects

Table 5.5 provides a summary of the effects of training load after adjusting for previous leg injuries. The effects of high training load on the risk of injuries increased by an average of 20% after adjusting for previous leg injuries when compared to the individual (unadjusted) effects of training load (Table 5.2). The only notable exceptions were sRPE rolling average ACWR and sRPE smoothed ACWR, where the effects decreased by approximately 15% and 10%, respectively, after adjusting for previous leg injuries. Table 5.5 also shows the effects of a combination of high training load and a recent leg injury where the increase in risk of injuries was considerably larger than the individual effects of each of these high-risk conditions.

Substantial individual differences in injury risk existed even after accounting for training load and history of previous leg injuries. For example, injury-prone players were at a more than five times higher risk of injuries compared to the robust players after adjusting for a 14-d smoothed Player Load and previous leg injuries (hazard ratio 5.4, 90% confidence limits 3.6–12). Similar differences of more than five times were observed after adjusting for other derived measures of training load.

Table 5.5. Effects of training load adjusted for history of previous leg injuries and combined with a history of a recent leg injury derived from part two of the analysis.^a

| Derived measure | Level | sRPE | Player Load | Total distance | High-intensity running distance |
|----------------------|---------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| 7-d rolling average | High | 0.59%, 2.2 (1.31-3.7)*** | 0.54%, 1.70 (1.05-2.7)** | 0.50%, 1.54 (0.94-2.5)** | 0.48%, 1.60 (0.96-2.7)** |
| | Moderate-high | 0.38%, 1.43 (0.82-2.5)** | 0.25%, 0.79 (0.44-1.39) | 0.33%, 1.01 (0.59-1.73) | 0.40%, 1.35 (0.80-2.3) |
| | Moderate-low | 0.29%, 1.09 (0.61-1.94) | 0.39%, 1.22 (0.73-2.0) | 0.36%, 1.13 (0.67-1.90) | 0.34%, 1.15 (0.67-1.97) |
| | Low | 0.27%, Reference | 0.32%, Reference | 0.32%, Reference | 0.30%, Reference |
| | High + RLI | 0.91%, 5.0 (2.3-11)**** | 0.79%, 3.6 (1.70-7.6)**** | 0.73%, 3.3 (1.56-7.2)**** | 0.71%, 3.5 (1.61-7.7)*** |
| 14-d rolling average | High | 0.79%, 2.6 (1.61-4.3)**** | 0.68%, 2.3 (1.38-3.7)*** | 0.71%, 2.2 (1.35-3.5)*** | 0.73%, 2.4 (1.45-3.9)*** |
| | Moderate-high | 0.32%, 1.05 (0.59-1.87) | 0.31%, 1.04 (0.59-1.82) | 0.29%, 0.89 (0.50-1.56) | 0.40%, 1.29 (0.75-2.23) |
| | Moderate-low | 0.20%, 0.66 (0.35-1.25) | 0.28%, 0.92 (0.52-1.64) | 0.25%, 0.77 (0.43-1.37) | 0.18%, 0.58 (0.30-1.12) |
| | Low | 0.30%, Reference | 0.30%, Reference | 0.33%, Reference | 0.31%, Reference |
| | High + RLI | 1.27%, 6.3 (2.9-14)**** | 1.01%, 5.0 (2.3-11)**** | 1.05%, 4.8 (2.3-10)**** | 1.13%, 5.6 (2.6-12)**** |
| 21-d rolling average | High | 0.55%, 1.82 (1.11-3.0)** | 0.40%, 1.34 (0.79-2.3) | 0.35%, 1.17 (0.68-2.00) | 0.55%, 1.68 (1.03-2.7)** |
| | Moderate-high | 0.26%, 0.87 (0.49-1.54) | 0.48%, 1.58 (0.95-2.6)** | 0.55%, 1.81 (1.12-3.0)*** | 0.37%, 1.11 (0.66-1.87) |
| | Moderate-low | 0.42%, 1.39 (0.84-2.3) | 0.35%, 1.17 (0.69-1.99) | 0.33%, 1.08 (0.63-1.84) | 0.31%, 0.92 (0.54-1.59) |
| | Low | 0.30%, Reference | 0.30%, Reference | 0.30%, Reference | 0.33%, Reference |
| | High + RLI | 0.80%, 4.1 (1.88-8.9)*** | 0.89%, 3.0 (1.37-6.8)** | 0.51%, 2.6 (1.17-5.9)** | 0.81%, 3.9 (1.78-8.4)**** |
| 28-d rolling average | High | 0.45%, 1.31 (0.80-2.1) | 0.39%, 1.35 (0.80-2.3) | 0.37%, 1.37 (0.80-2.34) | 0.51%, 1.90 (1.13-3.2)*** |
| | Moderate-high | 0.30%, 0.88 (0.52-1.49) | 0.38%, 1.31 (0.78-2.2) | 0.38%, 1.43 (0.84-2.42) | 0.38%, 1.41 (0.83-2.4) |
| | Moderate-low | 0.34%, 0.98 (0.59-1.63) | 0.36%, 1.25 (0.74-2.1) | 0.41%, 1.52 (0.91-2.6)** | 0.29%, 1.10 (0.62-1.92) |
| | Low | 0.34%, Reference | 0.29%, Reference | 0.27%, Reference | 0.27%, Reference |
| | High + RLI | 0.67%, 2.8 (1.29-6.2)*** | 0.59%, 3.0 (1.33-6.6)** | 0.54%, 3.0 (1.32-6.7)** | 0.78%, 4.4 (1.95-9.7)**** |
| 7-d smoothed | High | 0.75%, 3.1 (1.85-5.3)**** | 0.76%, 3.4 (2.0-5.9)**** | 0.77%, 3.1 (1.84-5.2)**** | 0.77%, 3.2 (1.88-5.3)**** |
| | Moderate-high | 0.26%, 1.06 (0.57-1.99) | 0.31%, 1.37 (0.74-2.6) | 0.28%, 1.13 (0.61-2.1) | 0.25%, 1.03 (0.55-1.92) |
| | Moderate-low | 0.31%, 1.29 (0.72-2.3) | 0.27%, 1.21 (0.64-2.3) | 0.27%, 1.09 (0.52-2.0) | 0.29%, 1.19 (0.65-2.16) |
| | Low | 0.24%, Reference | 0.22%, Reference | 0.25%, Reference | 0.25%, Reference |
| | High + RLI | 1.15%, 7.3 (3.3-16)**** | 1.12%, 7.9 (3.5-18)**** | 1.12%, 7.1 (3.2-16)**** | 1.15%, 7.3 (3.3-16)**** |
| 14-d smoothed | High | 0.63%, 2.9 (1.68-5.1)**** | 0.71%, 4.2 (2.3-7.6)**** | 0.69%, 4.1 (2.3-7.4)**** | 0.65%, 3.8 (2.1-7.0)**** |
| | Moderate-high | 0.46%, 2.2 (1.22-3.8)*** | 0.25%, 1.49 (0.75-3.0) | 0.30%, 1.79 (0.93-3.5)** | 0.43%, 2.5 (1.35-4.8)*** |
| | Moderate-low | 0.26%, 1.22 (0.65-2.3) | 0.41%, 2.4 (1.31-4.5)** | 0.39%, 2.3 (1.22-4.3)** | 0.32%, 1.84 (0.95-3.6)** |
| | Low | 0.21%, Reference | 0.17%, Reference | 0.17%, Reference | 0.17%, Reference |

| | | | | | |
|----------------------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| | High + RLI | 0.99%, 7.1 (3.1-16) **** | 1.06%, 9.8 (4.3-23) **** | 1.03%, 9.7 (4.2-22) **** | 0.99%, 9.2 (3.9-22) **** |
| 28-d smoothed | High | 0.51%, 2.2 (1.26-3.8) *** | 0.57%, 3.4 (1.81-6.2) **** | 0.57%, 3.4 (1.80-6.3) **** | 0.68%, 3.5 (1.99-6.3) **** |
| | Moderate-high | 0.44%, 1.87 (1.07-3.3) ** | 0.44%, 2.6 (1.37-4.9) *** | 0.49%, 2.9 (1.55-5.5) *** | 0.31%, 1.58 (0.83-3.01) |
| | Moderate-low | 0.35%, 1.51 (0.86-2.7) | 0.39%, 2.3 (1.22-4.4) *** | 0.34%, 2.0 (1.05-3.9) ** | 0.39%, 2.0 (1.10-3.7) ** |
| | Low | 0.23%, Reference | 0.17%, Reference | 0.17%, Reference | 0.19%, Reference |
| | High + RLI | 0.78%, 5.1 (2.2-11) **** | 0.86%, 8.2 (3.5-19.7) **** | 0.87%, 8.4 (3.5-20) **** | 1.04%, 8.5 (3.7-20) **** |
| Rolling average ACWR | High | 0.54%, 1.81 (1.12-2.9) *** | 0.56%, 2.5 (1.50-4.3) **** | 0.56%, 2.8 (1.48-3.9) **** | 0.46%, 1.30 (0.81-2.1) |
| | Moderate-high | 0.30%, Reference | 0.22%, Reference | 0.20%, Reference | 0.36%, Reference |
| | Moderate-low | 0.29%, 0.96 (0.57-1.67) | 0.38%, 1.72 (0.98-3.0) ** | 0.44%, 2.3 (1.27-4.0) *** | 0.35%, 0.98 (0.58-1.64) |
| | Low | 0.30%, 1.01 (0.59-1.75) | 0.23%, 1.02 (0.54-1.92) | 0.22%, 1.14 (0.60-2.2) | 0.22%, 0.62 (0.35-1.10) |
| | High + RLI | 0.77%, 3.7 (1.78-7.8) *** | 0.82%, 5.4 (2.5-12) **** | 0.79%, 5.8 (2.7-12.5) **** | 0.70%, 2.8 (1.36-5.9) ** |
| Smoothed ACWR | High | 0.70%, 3.6 (2.1-6.1) **** | 0.83%, 8.0 (3.9-17) **** | 0.83%, 8.1 (3.9-17) **** | 0.79%, 5.1 (2.8-9.4) **** |
| | Moderate-high | 0.19%, Reference | 0.10%, Reference | 0.10%, Reference | 0.16%, Reference |
| | Moderate-low | 0.25%, 1.27 (0.68-2.3) | 0.25%, 2.4 (1.06-2.6) ** | 0.28%, 2.7 (1.19-6.3) *** | 0.32%, 2.1 (1.04-4.0) ** |
| | Low | 0.34%, 1.75 (0.99-3.1) ** | 0.35%, 3.3 (1.54-7.7) *** | 0.32%, 3.1 (1.41-6.7) *** | 0.26%, 1.67 (0.82-3.3) |
| | High + RLI | 0.93%, 6.8 (3.2-14) **** | 1.13%, 16 (6.4-40) **** | 1.12%, 16 (6.4-40) **** | 1.09%, 10 (4.6-23) **** |
| Monotony | High | 0.55%, 1.63 (1.00-2.7) ** | 0.61%, 2.5 (1.48-4.1) *** | 0.60%, 3.1 (1.81-5.3) **** | 0.67%, 2.6 (1.56-4.2) **** |
| | Moderate-high | 0.36%, 1.06 (0.63-1.80) | 0.31%, 1.24 (0.72-2.14) | 0.29%, 1.48 (0.82-2.7) | 0.23%, 0.86 (0.48-1.57) |
| | Moderate-low | 0.28%, 0.84 (0.48-1.47) | 0.30%, 1.21 (0.72-2.04) | 0.39%, 1.98 (1.18-3.4) *** | 0.31%, 1.17 (0.69-1.98) |
| | Low | 0.34%, Reference | 0.25%, Reference | 0.19%, Reference | 0.26%, Reference |
| | High + RLI | 0.81%, 3.6 (1.69-7.5) *** | 0.91%, 5.4 (2.4-12.1) **** | 0.90%, 6.9 (3.0-16) **** | 1.02%, 5.7 (2.6-12) **** |
| Strain | High | 0.61%, 1.91 (1.18-3.1) *** | 0.58%, 2.1 (1.28-3.6) ** | 0.50%, 1.69 (1.01-2.8) ** | 0.59%, 2.2 (1.29-3.6) *** |
| | Moderate-high | 0.36%, 1.13 (0.66-1.92) | 0.36%, 1.31 (0.75-2.3) | 0.41%, 1.38 (0.81-2.4) | 0.33%, 1.22 (0.69-2.2) |
| | Moderate-low | 0.24%, 0.76 (0.42-1.36) | 0.30%, 1.09 (0.61-1.95) | 0.30%, 1.00 (0.56-1.76) | 0.33%, 1.20 (0.68-2.1) |
| | Low | 0.32%, Reference | 0.27%, Reference | 0.30%, Reference | 0.27%, Reference |
| | High + RLI | 0.92%, 4.3 (2.0-9.1) **** | 0.89%, 4.9 (2.2-11) **** | 0.77%, 3.9 (1.77-8.5) **** | 0.91%, 5.0 (2.3-11) **** |

^aValues are injury hazard (risk per player per exposure day), hazard ratio (with 90% confidence limits). Substantial effects are in bold.

Likelihood of increased risk of injuries: * *possibly*, ** *likely*, *** *very likely*, **** *most likely*.

RLI, recent leg injury; sRPE, session rating of perceived exertion; ACWR, acute-to-chronic workload ratio.

The effects of high-risk levels for professional experience, sit-and-reach test, adductor squeeze tests, and mood after adjusting for training load and history of previous leg injuries are summarized in Table 5.6. Negligible differences in the hazard ratio of <5% were observed between the individual and adjusted effects for these high-risk levels. The combined effects of each of these high-risk levels with high training load and a recent leg injury are also shown in Table 5.6. Extremely large increases in the risk of injuries were observed when multiple risk factors were combined.

Substantial proportions of the effects of high ACWR were explained by acute loads and previous leg injuries. The effect of high sRPE rolling average ACWR decreased by 28% from hazard ratio of 2.1 (90% confidence limits 1.32–3.3) to 1.50 (0.90–2.52) after adjusting for acute load (sRPE 7-d rolling average) and previous leg injuries. Similarly, the effect of high sRPE smoothed ACWR decreased by 38% from 4.0 (2.4–6.7) to 2.5 (1.4–4.5) after adjusting for acute load (sRPE 7-d smoothed) and previous leg injuries.

Table 5.6. The adjusted and combined effects of professional experience, musculoskeletal screening, and subjective wellness on the risk of injuries derived from part three of the analysis.^a

| Selected variable | Level | Effect adjusted for acute load and history of previous leg injuries | Combined effect ^b as compared to the lowest risk scenario | Combined effect ^b as compared to the regular scenario |
|--------------------------|----------------|---|--|--|
| Professional experience | 7+ years | 0.52%, 1.92 (1.04-3.6)** | 1.64%, 15 (5.5-40)**** | 1.64%, 7.7 (3.5-17)**** |
| Sit-and-reach test | Z-score < -1.5 | 0.49%, 2.5 (1.40-4.4)** | 2.11%, 24 (8.2-68)*** | 2.11%, 17 (7.4-40)*** |
| Adductor squeeze test 0 | Z-score < -1.5 | 0.41%, 1.98 (1.03-3.8)** | 1.77%, 19 (6.2-57)*** | 1.77%, 14 (5.6-35)*** |
| Adductor squeeze test 45 | Z-score < -1.5 | 0.35%, 1.66 (0.86-3.2) | 1.52%, 16 (5.3-49)**** | 1.52%, 12 (4.7-29)**** |
| Adductor squeeze test 90 | Z-score < -1.5 | 0.51%, 2.9 (1.72-4.9)**** | 2.36%, 31 (11-89)**** | 2.36%, 22 (9.7-52)**** |
| Mood | Z-score < -1.5 | 0.65%, 1.99 (1.08-3.7)** | 2.12%, 15 (5.3-41)*** | 2.12%, 9.5 (4.0-23)*** |

^aValues are injury hazard (risk per player per exposure day), hazard ratio (with 90% confidence limits). Substantial effects are in bold.

^bCombined with high acute load and a recent leg injury.

Likelihood of increased risk of injuries: * *possibly*, ** *likely*, *** *very likely*, **** *most likely*.

5.4 Discussion

High absolute and relative measures of internal and external training load were associated with increased risk of injuries, and the magnitudes of the effects were considerably influenced by history of previous injuries. The effects for training load measures derived using exponentially weighted moving averages were typically larger than the effects for similar measures derived using rolling averages. A substantial proportion of the effects of high ACWR was explained by acute load and history of previous injuries. Having 7+ years of professional experience and substantial reductions in sit-and-reach test, adductor squeeze tests, and mood were also associated with a higher risk of injuries, and the effects of these risk factors were not confounded by training load and history of previous injuries. Combinations of multiple risk factors were associated with extremely large increases in the risk of injuries.

5.4.1 Training load

Training induces physiological and biomechanical stress on physiological systems and body tissues. Accumulation of the negative effects of such stressors through vigorous training and/or inadequate recovery results in a reduced stress-bearing capacity of the tissues and a higher chance of failure of the adaptive mechanisms and injury (Kumar, 2001; Vanrenterghem et al., 2017). This process can explain the observed associations between high cumulative loads and increased risk of injuries, which is consistent with previous findings in various football codes (Cross et al., 2016; Malone et al., 2017; Rogalski et al., 2013). In the present study, the effects of high training load increased after adjusting for history of previous leg injuries. An injury episode results in low cumulative loads

as the injured player goes through the rehabilitation and return to play process. A recently injured player is inherently at a higher risk of injuries upon return to play (Toohey et al., 2017), and as a result, the injury hazard for purely low training load tends to be overestimated. In other words, a proportion of the estimated injury hazard in the low training load level is due to the effects of recent injuries. In the current study, accounting for history of previous leg injuries led to a lower estimate of injury hazard for low training load (which served as the reference level) and a higher injury hazard for high training load compared to the unadjusted (individual) values. These changes in turn translated into larger effects (hazard ratios) for high training load.

The only derived measures where adjusting for previous leg injuries resulted in smaller effects for the high levels were sRPE rolling average ACWR and sRPE smoothed ACWR. The effects were further reduced after making adjustments for acute load. High acute load and previous injuries are known injury risk factors, which may contribute to a high ACWR, and in the current study a substantial proportion of the effects of high ACWR on the increased risk of injuries is explained by these variables. Nevertheless, the associations between high ACWR and increased risk of injuries remained substantial even after adjusting for acute load and previous leg injuries, indicating that a high ACWR may represent a high-risk condition that is not identified by monitoring only acute load and previous injuries. Researchers and practitioners are advised to consider the reasons behind a high ACWR when interpreting their data. In addition, moderate-high levels of smoothed ACWR (as defined in Table 5.1) were associated with substantially lower risk of injuries compared to other levels even after adjusting

for previous leg injuries. Similar protective effects have been observed for moderate-high rolling average ACWRs in rugby league and soccer (Hulin, Gabbett, Caputi, et al., 2016; Malone et al., 2017).

In contrast to the sRPE-derived ACWRs, the effects of high GPS/accelerometer-derived ACWRs increased after adjusting for previous leg injuries. This unexpected finding is likely due to the fact that the majority of training for injured players during the rehabilitation period cannot be captured using the GPS/accelerometer units, resulting in inconsistent ACWRs at the early stages of return to full training. A number of studies have attempted to address this limitation by removing high ACWRs from the analysis when chronic loads were more than 1 SD or 2 SD below the mean, which limits the application of ACWR following an injury episode (Carey et al., 2017; Hulin et al., 2014; Hulin, Gabbett, Lawson, et al., 2016). More research is required to better understand and address the issue of inconsistent ACWRs post-injury, especially for GPS/accelerometer-derived variables.

It should be noted that the training load of each day was included in calculation of the derived training load measures on that day. This step is important for practitioners and studies with a daily design, in view of the weekly periodization of training in elite settings. For example, high cumulative loads derived from previous days would not be a concern, when only a light recovery session is planned on a given day. Only seven of the 65 injuries in the current study resulted in the injured player completing substantially lower training load than originally planned on the day of injury, which along with the daily analysis of data, minimized the risk of associating artificially low derived measures with injury

incidences. The derived training loads in the current study represent the actual workloads completed by players up to the moment of sustaining an injury. To apply this method in practice, an estimated training load of the upcoming day should be used to calculate the derived measures, in order to evaluate the load and injury risk of individual players, should they proceed to complete the training day as planned. The resulting information can then be used in the decision-making process in regards to training modification or team selection for individual players (Charlton, Ilott, Borgeaud, & Drew, 2017). Several studies with weekly designs have similarly evaluated the effects of training load on injuries in the current week (Hulin, Gabbett, Lawson, et al., 2016; Murray, Gabbett, Townshend, Hulin, et al., 2017; Windt, Gabbett, et al., 2017). The limited data availability did not allow for splitting the derived training load measures into more than four levels for analysis. However, practitioners may further subdivide the training load levels to differentiate between high, very high, and extremely high derived training loads, which will provide additional practically relevant information. It is also possible that extreme values of some training load constructs are more sensitive than others in detecting high risk of injuries (Vanrenterghem et al., 2017).

5.4.2 Exponentially weighted moving averages versus rolling averages

This study is the first to have evaluated the effects of cumulative loads derived using both exponentially weighted moving averages and rolling averages on the risk of injuries. The results demonstrated that cumulative load calculated using exponentially weighted moving averages is a better alternative to rolling average cumulative load in evaluating the risk of injuries. Similar conclusions can be made in regards to ACWRs. A recent study also found that exponentially weighted

moving average ACWR (a relative measure of training load) was a more sensitive indicator of injury likelihood in Australian football than rolling average ACWR (Murray, Gabbett, Townshend, & Blanch, 2017). Exponentially weighted moving averages take into account the physiological principle that the effects of a training stimulus decay over time, while rolling averages assign the same level of importance to all observations in a time period (Hawley, 2002; Menaspa, 2017a). This emerging method of deriving training load has shown promising applications in evaluation of match performance (Lazarus et al., 2017) and injury prevention (Murray, Gabbett, Townshend, & Blanch, 2017). In the current study, the 14-d time period for cumulative smoothed loads (decay factor=0.07) had the largest associations with the risk of injuries. Differences between sports in activity profile, training periodization, and competition schedule (Gamble, 2006; Varley et al., 2014) may result in other decay factors to perform better under such different circumstances. Researchers are encouraged to explore with various decay factors to identify the one that works best in their sport and cohort of athletes.

5.4.3 History of previous injuries

History of previous injuries is a well-recognized injury risk factor and has been evaluated from two main perspectives. Recurrent injuries refer to the same injury type to the same site as the index (initial) injury, while subsequent injuries may or may not differ from the index injury in nature or location (Finch & Cook, 2014; Finch et al., 2017). The current study evaluated the effects of any previous injuries and previous leg injuries on subsequent soft tissue non-contact leg injuries, and found that recent injury history was associated with a substantial increase in the risk of injuries. History of previous leg injuries had a slightly larger

effect on injury risk compared to the history of any previous injuries, as only soft tissue non-contact leg injuries were considered for analysis in the current study. The number of days since return to full training was used as a method of accounting for decaying effects of previous injuries.

The presented results are in line with previous findings where recent injuries have a larger effect on injury recurrence compared to previous non-recent injuries (Orchard, 2001; Orchard, Kountouris, & Sims, 2017). Complete resolution of deficits resulting from an injury episode may extend beyond the time of return to play (Orchard & Best, 2002; Verrall et al., 2006). Such deficits include reduced muscular strength and flexibility, proprioception, and general fitness, as well as altered running biomechanics and motor control (Dauty et al., 2003; Lee et al., 2009; Maniar et al., 2016; Mujika & Padilla, 2000), which collectively contribute to a higher risk of subsequent injuries in athletes with a history of a recent injury (Toohey et al., 2017).

There is a need for studies that make appropriate adjustments for potential confounders in evaluating athletes' injury risk profile (Toohey et al., 2017; Windt, Zumbo, Sporer, MacDonald, & Gabbett, 2017). The current study found history of previous injuries to be a positive confounder (Meeuwisse, 1994g) for sRPE-derived ACWR and a negative confounder (Meeuwisse, 1994g) for other derived measures of training load. Studies investigating the effects of training load on injury risk should adjust for the decaying effects of previous injuries in order to obtain more accurate estimates.

5.4.4 Professional experience

Players with 7+ years of professional experience were at a higher risk of injuries compared to the players with 3–6 years of professional experience. A number of AFL studies have reported similar findings, where more experienced players had a higher risk of injuries compared to the less experienced players (Colby, Dawson, Peeling, et al., 2017; Gabbe, Bennell, & Finch, 2006; Rogalski et al., 2013). The body's adaptive capacity in response to a training stimulus as well as the ability to recover from fatigue are thought to diminish as professional experience and therefore age increase (Maffey & Emery, 2007); however, little quality evidence specific to athletes exists to support these plausible speculations.

History of previous injuries has been identified as a confounder for age, as older players have likely sustained more injuries over their career, which may have predisposed them to subsequent injuries (Arnason et al., 2004). In the current study, the effects of professional experience did not change substantially after adjusting for training load and history of previous injuries, possibly due to the fact that the records of history of previous injuries extended only as far as the season prior to the study period rather than the entire professional career of individual players. The current results indicate that the effects of professional experience on injury risk are independent from the effects of training load and history of injuries over the current and previous season. Professional experience remains an important factor to consider in relation to load management and injury prevention in professional athletes.

5.4.5 Musculoskeletal screening

Substantial reductions in the sit-and-reach and adductor squeeze test scores were associated with an increased risk of injuries. The effects of musculoskeletal screening scores on the risk of injuries have been evaluated mostly in the form of pre-season screening. A limitation of this approach is that pre-season test scores reflect the condition of athletes only at that particular time (Whiteley, 2016). Musculoskeletal screening scores of elite Australian footballers have shown substantial week-to-week variations throughout the season (Chapter 4). Variation in the scores obtained from regular musculoskeletal screening, rather than the absolute values, may better reflect the condition of athletes, their response to prescribed training, and subsequently the risk of injuries (Paul et al., 2014; Thorpe et al., 2017). The presented findings provide evidence for these previous speculations on application of weekly musculoskeletal screening for injury prevention purposes. Larger reductions in the test scores (>1.5 SD vs. >1 SD) had slightly larger effects on the risk of injuries. Practitioners may use both these thresholds in a multi-level flagging system.

One study to date has evaluated the effects of substantial reductions (>1 SD) in weekly musculoskeletal screening scores on the risk of injuries in elite Australian footballers, and did not find substantial associations between these variables (Colby, Dawson, Peeling, et al., 2017). In this study, rolling season-to-date standard deviations were used to determine substantial reductions in the test scores, while in the current study, the pool of scores at each season phase of each season was used for this purpose. Creating z-scores using the rolling season-to-date approach may result in inconsistent scores at early stages of the

season (Robertson et al., 2017). This methodological dissimilarity as well as possible differences in the implemented interventions in response to the screening scores can explain the difference in findings between the two studies.

The effects of reductions in screening scores did not substantially change after adjusting for the effects of previous leg injuries and training load. The screening tests in the current study were conducted immediately prior to the first field training session of the week, which was planned on day two or three after a match (or main training session during pre-season). Changes in screening scores following matches generally return back to baseline within two days (Dawson et al., 2005; McLellan et al., 2011; Wollin et al., 2017). Musculoskeletal screening tests conducted 2-3 days post-match are not sensitive to training load (Chapter 4), which can explain the similarity between the unadjusted and adjusted effects of reductions in screening scores. Training load and previous leg injuries did not confound the effects of reductions in screening scores.

5.4.6 Subjective wellness

Substantial reductions in mood were associated with increased risk of injuries, while no substantial effects were observed for similar reductions in the scores (feeling worse) for perceived fatigue, sleep quality, and stress. In addition, worse scores for general muscle soreness were associated with a lower risk of injuries. The likely reason behind such inconsistencies is the combination of changes in wellness scores in a weekly cycle and the daily analysis design used in the current study. Wellness scores are generally at their lowest at early stages following a match (or the main training session during pre-season), and gradually return back to baseline before the next match (Gallo et al., 2017; Thorpe et al.,

2016). The wellness z-scores in the current study were created from the pool of the data for each item at each season phase for individual players. As a result, generally lower scores obtained earlier in a week coincided with light recovery sessions that inherently have a lower risk of injuries. On the other hand, typically higher wellness scores could have been recorded later in the week and before matches or main training sessions, which carry a higher risk of injuries. Future studies with larger sample sizes should evaluate the effects of changes in wellness scores on the risk of injuries while comparing the wellness scores on a given day to previous scores obtained on similar days of the weekly cycle (e.g., creating z-scores of each day post-match separately). It is also possible that the implemented interventions in response to the wellness scores at this elite environment mitigated the risk of injuries and contributed to the observed inconsistencies.

5.4.7 The combined effects and decision-making

The multivariate and complex nature of sports injuries has repeatedly been emphasized in the literature (Bahr & Holme, 2003; Bittencourt et al., 2016; Meeuwisse, 1994a). The results of the current study indicate that combinations of multiple risk factors result in extremely large increases in the risk of injuries. One study with a weekly design recently evaluated the effects of multiple variables similar to the ones investigated in the current study on the risk of injuries (Colby, Dawson, Peeling, et al., 2017). The authors found that the predictive accuracy of the multivariate model (as measured via the area under curve) was substantially better than all the univariate models when tested against data that was used to develop the model (in-sample data). While history of previous injuries

was not evaluated in this study, interactions between low chronic workloads and very high rolling average ACWRs were associated with increased risk of injuries in the subsequent week. The results of the current study are in agreement with these findings, when it is taken into consideration that a key contributor to low chronic workloads is recent injuries.

An important issue to consider in the decision-making process for injury prevention in an elite sports setting is the cost-benefit analysis of training and match participation for individual players (Gabbett, Windt, & Gabbett, 2016). To better apply this concept, the absolute injury hazards associated with individual and combined risk factors should be considered in addition to the hazard ratios, along with the concept of acceptable injury risk (Charlton et al., 2017; Creighton et al., 2010; Orchard, Best, & Verrall, 2005). In a hypothetical scenario based on the findings presented in Tables 5.2 to 5.6 in regards to the injury hazards provided for a given day, a player with high acute cumulative load (as defined in this study and not extremely high), will have a less than 5% chance of sustaining a soft tissue non-contact injury over seven exposure days if he remains in this high acute load level during this period. This scenario may not warrant an aggressive training modification, considering the low absolute risk of injury and the likely benefits of training and match participation over this period. It should also be noted that an injury risk of between 1.5–2% remains for other levels of acute load for the same period, which can be considered as the inherent risk of participating in physical activity at elite level. In a second scenario, the high acute cumulative load is accompanied by a recent leg injury and substantial reductions in the musculoskeletal screening scores. The injury risk now increases to over

15% over the next seven exposure days based on the findings presented in Table 5.6. These examples highlight the importance of simultaneous consideration of multiple risk factors. The results also demonstrated that injury-prone players are at a more than five times higher risk of injuries compared to robust players after accounting for training load and previous injuries. Consequently, in the second scenario the actual risk for the same period would be more than 25% for an injury-prone player and less than 5% for a robust player. As evident from these hypothetical scenarios, and in agreement with previous recommendations (Charlton et al., 2017; Gabbett et al., 2017), the numbers stemming from athlete monitoring practices cannot replace the medical and conditioning staffs' expertise and knowledge of players. Prediction of injuries as a binary outcome (yes/no) has not yet been shown to possess the required accuracy, especially when tested against out-of-sample data (Carey et al., 2018; Colby, Dawson, Peeling, et al., 2017; Fanchini et al., 2018). However, estimation of injury risk for individual players on a given day as a probability may assist practitioners with making better informed decisions in the quest for minimizing injury risk and maximizing athletic performance. Other factors potentially influencing such decisions include the stage of the season, the coach's philosophy, availability of quality substitute players, competition schedule, and quality of the opposition (Charlton et al., 2017; Creighton et al., 2010; Orchard et al., 2005). A combination of training load, players' response to training, and other injury risk factors should be considered along with several decision modifiers to increase the chance of success for individual players and the team.

5.4.8 Limitations

The current study is effectively a case study of a single Australian football team over two consecutive seasons. While the explained concepts behind the findings of the current study likely apply to other Australian football clubs and team sports in general, the exact thresholds for predictors and magnitudes of effects may differ in other environments. Australian football clubs are not allowed to track training loads during the off-season period and Christmas break, which could have negatively affected the precision of the estimates (Buchheit, 2017). The z-scores for musculoskeletal screening and subjective wellness were calculated using the pool of data at each season phase of each season, which is a rather retrospective approach. This approach was taken to avoid obtaining likely inconsistent scores in the absence of enough historical data at early stages of each season phase (Robertson et al., 2017). In a practical setting, historical data from the previous season may be used at early stages of each season to overcome this limitation. The ACWR measures in our study were calculated using the coupled approach and the 7-28 day time windows, while the use of uncoupled approach and other time windows could potentially be more appropriate (Carey et al., 2017; Lolli et al., 2017; Windt & Gabbett, 2018). In our study, a rather large number of independent variables were evaluated and multiple comparisons were made, which automatically increase the risk of type I error (false positive). However, this limitation is not concerning here as the majority of the independent variables in our study (as opposed to only a small selection) showed substantial associations with injury risk.

5.5 Conclusion

High absolute and relative measures of training load were associated with increased risk of injuries. These effects were positively or negatively confounded by history of previous injuries. History of a recent injury, long-term experience at professional level, and substantial reductions in a selection of musculoskeletal screening and subjective wellness scores were also associated with increased risk of injuries. Combinations of multiple risk factors resulted in extremely large increases in the risk of injuries. The information from athlete monitoring practices should be interpreted collectively and used as a part of the injury prevention/player management process along with consideration of individual differences in the risk of injuries.

Chapter 6 – General discussion, conclusion, and future research

6.1 Introduction

Training is the systematic application of stress and recovery. Intensified periods of training aim to increase the physical capacity of athletes with the ultimate goal of improving athletic performance. Appropriate application of recovery aims to counter the negative effects of training such as the increase in fatigue and injury risk. The process of striking a balance between stress and recovery is facilitated by monitoring the stress dose (training load) and the response to the applied stress. This thesis aimed to provide an insight into several musculoskeletal adaptations in response to training in elite Australian footballers as well as the individual and combined effects of several athlete-monitoring-derived factors on the risk of injury. The injury causation models have evolved over the past few decades in acknowledgment of the multifactorial nature of injuries as well as the dynamic state of susceptibility to injury (Hulme & Finch, 2015; Meeuwisse, 1994a; Meeuwisse et al., 2007). The ever-changing risk of injury for individual athletes is a result of adaptations and maladaptations that stem from repeated sports participation throughout the season (Meeuwisse et al., 2007). The first two studies of this thesis focused on some of the musculoskeletal adaptations in elite Australian footballers over the pre-season and in-season periods, and evaluated the influence of training load on changes in tendon structure and weekly musculoskeletal screening scores. The third study focused on the multivariate nature of injuries and evaluated the individual and combined effects of training

load, changes in the musculoskeletal screening scores, history of previous injuries, subjective wellness, and professional experience on the risk of soft tissue non-contact injuries in a cohort of elite Australian footballers.

6.2 Changes in tendon structure over an intensified training period and the influence of training load

Pre-season is characterized by periods of high training load and is considered a high-risk phase for sustaining tendon injuries (Woods, Hawkins, Hulse, & Hodson, 2002). Ultrasound-detected tendon abnormalities are associated with an increased risk of developing tendinopathy symptoms (Docking et al., 2015; Fredberg et al., 2008; Malliaras & Cook, 2006). The development of a new technology in ultrasound tissue characterization (UTC) has allowed for quantification of subtle changes in tendon structure with promising applications in athlete monitoring and injury prevention (Docking et al., 2015; Docking et al., 2016). One study recently reported substantial improvements in the Achilles tendon structure of elite Australian footballers over the pre-season period (Docking et al., 2016); however, the effects of training load and leg dominance were not investigated, and it remained unknown whether a dose-response relationship exists between the applied training stress and changes in tendon structure. The current thesis built on previous findings by demonstrating improvements in the Achilles and patellar tendons of elite Australian footballers over the pre-season period and finding small and inconsistent effects for training load on changes in tendon structure (see Chapter 3). Players with injury episodes during pre-season were excluded from the analysis as interruptions to the planned training program and the possible effects of lower limb injuries (e.g.

altered lower limb biomechanics) could potentially influence changes in tendon structure over the pre-season. A similar (although more conservative) approach was taken in another study (Docking et al., 2016), which allowed for making direct comparisons between the findings. The overall training load of pre-season is not the main driver of adaptations and maladaptations in Achilles and patellar tendons. This finding is supported by a proposed continuum model of tendon pathology that allows for continual progression or regression of tendon along the pathology continuum based on a multitude of factors (Cook & Purdam, 2009; Cook, Rio, Purdam, & Docking, 2016). The recovery between tendon overloading sessions appears to be a key factor in determining whether adaptation or maladaptation occurs in response to repeated exposure to high training load of the pre-season period. The tendon response to load can be influenced by other factors such as genetics (September et al., 2009; September, Mokone, Schwellnus, & Collins, 2006), and as determined in the current thesis, leg dominance. The findings of this thesis indicate that appropriate application of recovery over intensified training periods can indeed nullify the undesirable effects of training on tendon structure. Ultrasound tissue characterization can be a valuable tool for athlete monitoring and injury prevention.

A limitation of the Chapter 3 is that tendon structure was only evaluated on two occasions; at the beginning and the end of pre-season with total pre-season training load included as a linear covariate. A greater potential of UTC appears to be in regular monitoring of tendons. Future studies should evaluate changes in tendon structure at shorter intervals (e.g. one week), the association of changes in tendon structure with the risk of developing symptoms, along with the

non-linear effects of training load. A detailed cost-benefit analysis also needs to be performed to determine whether regular monitoring of tendon structure for all athletes is justified, or the use of UTC as a regular monitoring tool should be limited to athletes who are at a higher risk of developing tendinopathies (e.g. athletes with a history of tendinopathy). Weekly musculoskeletal screening is an example of regular monitoring tools that evaluates other aspects of the musculoskeletal system to ensure maladaptations are avoided at shorter time intervals.

6.3 Weekly musculoskeletal screening in team sports

Previous research on musculoskeletal screening has predominantly focused on pre-participation screening. This format of screening does not account for the dynamic nature of adaptations and maladaptations to training as athletes repeatedly participate in the sport throughout the season. While regular screening has been proposed as a better alternative (Paul et al., 2014; Whiteley, 2016) and is currently being used by professional sports clubs (Colby, Dawson, Peeling, et al., 2017; Morgan et al., 2014), it had rarely been researched prior to this thesis. Normal variability of the screening scores throughout the season, individual differences in variability, and the influence of training load on changes in screening scores are some of the important aspects of weekly musculoskeletal screening that allow clinicians to better understand and interpret the information stemming from this athlete monitoring practice.

This thesis determined that substantial week-to-week variation in scores exists for the commonly used musculoskeletal tests throughout an Australian football league season, and clinicians using these tests should be aware of the normal

week-to-week variations when interpreting the screening scores (see Chapter 4). The substantial individual differences in variations identified in this thesis emphasised the need for an individualised approach in regards to interpretation of changes in screening scores, as prompted in a recent review (Robertson et al., 2017).

The current thesis also identified an important limitation of weekly musculoskeletal screening in that the scores are not sensitive to various absolute and relative measures of internal load when screening is conducted two or three days post-match (see Chapter 5). The transient changes in the musculoskeletal system in response to high acute load of a match generally return back to baseline levels by day two post-match in football code athletes (Dawson et al., 2005; McLellan et al., 2011; Wollin et al., 2017). The lack of sensitivity to training load and the timeline of change in the scores are suggestive of a limited value for weekly musculoskeletal screening as a measure of recovery. On the other hand, these limitations also indicate that substantial reductions in the screening scores point towards potentially important underlying issues that should be further investigated by medical staff. In addition, substantial associations existed between reductions in the weekly screening scores and risk of injuries (see Chapter 5), highlighting the merits of regular screening in elite team sports as an injury prevention strategy. Despite all the athlete monitoring and injury prevention efforts in elite sports settings, maladaptations to training stress may still occur. Understanding the contribution of training stress, maladaptive responses to training, and a multitude of modifying factors to occurrence of injury is a crucial step in refining injury prevention practices and strategies.

6.4 The individual and combined effects of injury risk factors

Training load is a reflection of the physiological and biomechanical stress imposed on athletes. Evaluation of training load as an injury risk factor has received much attention in recent years, and training load monitoring is now common practice in elite sports (Akenhead & Nassis, 2016; Drew & Finch, 2016; Taylor et al., 2012). However, the multifactorial nature of injuries and the dynamic state of athletes' response to training have rarely been incorporated in the design of studies investigating the effects of training load on the risk of injury. A further complication to this issue was that some well-established injury risk factors such as history of previous injuries were theorized to affect the relationship between training load and risk of injury (Blanch & Gabbett, 2016). Study 3 of this thesis (Chapter 5) specifically focused on addressing these gaps in the literature.

This thesis determined that combinations of multiple risk factors result in extremely large increases in the risk of injury. The identified risk factors for soft tissue non-contact injuries in elite Australian footballers were high absolute and relative measures of training load, history of a recent injury, long-term experience at professional level, and substantial reductions in a selection of musculoskeletal screening and subjective wellness scores. These findings further highlight the multifactorial nature of injuries and the importance of simultaneous consideration of multiple risk factors in the risk management of individual athletes in elite team sport environments. While the majority of previous studies have identified high cumulative load as an injury risk factor, several studies have found trivial/unclear effects and in some cases protective effects for high cumulative load (see Table 2.2). The findings of this thesis indicate that a key contributor to these

inconsistencies is the fact that none of the previous studies have accounted for the decaying effects of previous injuries. Previous injuries and in particular recent injuries are associated with an increased risk of injury (Orchard, 2001; Orchard et al., 2001; Toohey et al., 2017), while concurrently resulting in changes in the distribution of training and amounts of cumulative load in injured athletes (Ritchie, Hopkins, Buchheit, Cordy, & Bartlett, 2015). This thesis found history of previous injuries to be a positive confounder for some relative measures of training load (session RPE derived acute-to-chronic workload ratios) and a negative confounder for other absolute and relative measures of training load (Chapter 5). Accordingly, future studies need to account for the decaying effects of previous injuries while evaluating the effects of training load and other injury risk factors on the risk of injury.

The findings of this thesis also highlight the importance of evaluating the absolute risk of injury associated with injury risk factors rather than merely focusing on the effect statistics (ratios). While the significance of absolute injury risk has largely been overlooked in the literature, a number of recent studies have described the importance and application of this statistic in the management of individual athletes and the decision-making process for injury prevention purposes (Charlton et al., 2017; Gabbett et al., 2016; Toohey et al., 2017). Estimation of the absolute risk allows practitioners to make better informed decisions surrounding injury prevention practices for individual athletes, based on the cost-benefit analysis of sports participation.

It should be noted that the discussed findings are based on data from only one Australian football club. Future studies need to apply the developed concepts and

methodologies in studies with athletes from other sports and levels of competition to evaluate the generalizability of the findings. The potential impact of the findings of this thesis on day to day injury prevention decisions and outcomes in elite team sports also need to be evaluated in future research.

This thesis has provided a framework for the monitoring of team sport athletes to ensure a better application of stress and reduce the now much better understood risk of injury.

6.5 Practical applications

The practical applications of this thesis are:

- Ultrasound tissue characterization is a valuable tool for monitoring adaptations and maladaptations of tendons in elite athletes.
- Achilles and patellar tendons of elite Australian footballers can tolerate the high training load of the pre-season period.
- Leg dominance should be considered as a factor affecting the tendon response to training load.
- Weekly musculoskeletal screening is a valuable injury prevention strategy despite the limitations as a measure of recovery.
- Changes in musculoskeletal screening scores should be evaluated individually due to the substantial individual differences in week-to-week variations of the test scores.
- Multiple injury risk factors should be considered simultaneously in evaluation of the injury risk of individual athletes.

- Researchers should account for the decaying effects of training and history of previous injuries on injury risk.
- The absolute injury risk and individual differences in risk should be considered in the injury prevention decision-making process.

6.6 Conclusions

The specific conclusions of this thesis are:

- Achilles and patellar tendon structure of elite Australian footballers improve over the pre-season training period.
- The overall pre-season training load has small and inconsistent effects on changes in Achilles and patellar tendon structure over that period.
- The sit-and-reach test, dorsiflexion lunge test, and adductor squeeze tests have small to moderate week-to-week normal variability throughout an AFL season.
- Small individual differences in variability exists for the sit-and-reach test and adductor squeeze tests.
- Weekly musculoskeletal screening tests are not sensitive to measures of internal training load when conducted two or three days post-match.
- High internal and external training load, history of a recent injury, long-term experience at professional level, and substantial reductions in weekly musculoskeletal screening scores and mood are risk factors for soft tissue non-contact injuries in elite Australian footballers.
- Combinations of multiple risk factors are associated with extremely large increases in the risk of injury.

- Training load measures calculated using exponentially weighted moving averages are associated with larger increases in injury risk compared to measures derived using rolling averages.
- History of previous injuries is a confounder for the effects of training load.

Appendix A. UTC parameters and protocols

Adapted from Docking and Cook (2015)

A linear-array ultrasound transducer (SmartProbe 10L5, Terason 2000, Teratech, USA) mounted within a customized tracking device with motor drive and built-in acoustic standoff pad (UTC Tracker, UTC Imaging, Netherlands) was used to scan the Achilles and patellar tendons of the participants, which standardized the transducer tilt, gain, focus, and depth (10 MHz, focus = 1.3 cm, depth = 3 cm). The Achilles tendon was scanned with the participant standing on an elevated platform. The big toe and knee of the leg being scanned were placed against the wall in order to standardize the amount of ankle dorsiflexion. The patellar tendon was scanned with the participant lying in supine position and knee of the leg being scanned in ~60 degrees of flexion. Coupling gel was applied between the transducer, standoff pad, and skin to ensure maximum contact. Images were taken at 0.2 mm intervals over a 12cm distance. The stability of echopatterns was quantified over 25 images corresponding to a window of 4.8 mm. Regions of interest were selected at intervals of <5 mm from the disappearance of the calcaneus to the musculotendinous junction for Achilles tendon and from the inferior pole of the patella to the tibial tuberosity for patellar tendon.

References

- Akenhead, R., & Nassis, G. P. (2016). Training load and player monitoring in high-level football: current practice and perceptions. *International Journal of Sports Physiology and Performance*, 11(5), 587-593.
- Altman, D. G. (1990). *Practical statistics for medical research*: CRC press.
- Arnason, A., Andersen, T., Holme, I., Engebretsen, L., & Bahr, R. (2008). Prevention of hamstring strains in elite soccer: an intervention study. *Scandinavian Journal of Medicine and Science in Sports*, 18(1), 40-48.
- Arnason, A., Sigurdsson, S. B., Gudmundsson, A., Holme, I., Engebretsen, L., & Bahr, R. (2004). Risk Factors for Injuries in Football. *The American Journal Of Sports Medicine*, 32(1 suppl), 5S-16S. doi: 10.1177/0363546503258912
- Aughey, R. J. (2010). Australian football player work rate: evidence of fatigue and pacing? *International Journal of Sports Physiology and Performance*, 5(3), 394-405.
- Aughey, R. J. (2011a). Applications of GPS technologies to field sports. *International Journal of Sports Physiology and Performance*, 6(3), 295-310.
- Aughey, R. J. (2011e). Increased High-Intensity Activity in Elite Australian Football Finals Matches.
- Aughey, R. J. (2013). Widening margin in activity profile between elite and sub-elite Australian football: a case study. *Journal of Science and Medicine in Sport*, 16(4), 382-386.

- Aughey, R. J., Elias, G. P., Esmaeili, A., Lazarus, B., & Stewart, A. M. (2016). Does the recent internal load and strain on players affect match outcome in elite Australian football? *Journal of Science and Medicine in Sport*, 19(2), 182-186. doi: 10.1016/j.jsams.2015.02.005
- Bahr, R. (2016). Why screening tests to predict injury do not work—and probably never will...: a critical review. *British Journal of Sports Medicine*, 50(13), 776-780. doi: 10.1136/bjsports-2016-096256
- Bahr, R., & Holme, I. (2003). Risk factors for sports injuries--a methodological approach. *British Journal of Sports Medicine*, 37(5), 384-392. doi: 10.1136/bjism.37.5.384
- Bakken, A., Targett, S., Bere, T., Adamuz, M.-C., Tol, J. L., Whiteley, R., . . . Bahr, R. (2016). Health conditions detected in a comprehensive periodic health evaluation of 558 professional football players. *British Journal of Sports Medicine*, 50(18), 1142-1150. doi: 10.1136/bjsports-2015-095829
- Bakken, A., Targett, S., Bere, T., Eirale, C., Farooq, A., Tol, J. L., . . . Bahr, R. (2017). Interseason variability of a functional movement test, the 9+ screening battery, in professional male football players. *British Journal of Sports Medicine*, 51(14), 1081-1086. doi: 10.1136/bjsports-2016-096570
- Ball, K. (2013). Loading and performance of the support leg in kicking. *Journal of Science and Medicine in Sport*, 16(5), 455-459.
- Banister, E. W., Calvert, T. W., Savage, M. V., & Bach, T. M. (1975). A systems model of training for athletic performance. *Australian Journal of Sports Medicine*, 57-61.

- Bartlett, J. D., O'Connor, F., Pitchford, N., Torres-Ronda, L., & Robertson, S. J. (2017). Relationships between internal and external training load in team-sport athletes: evidence for an individualized approach. *International Journal of Sports Physiology and Performance*, 12(2), 230-234.
- Batt, M. E., Jaques, R., & Stone, M. (2004). Preparticipation examination (screening): practical issues as determined by sport: a United Kingdom perspective. *Clinical Journal of Sport Medicine*, 14(3), 178-182.
- Batterham, A. M., & Hopkins, W. G. (2006). Making meaningful inferences about magnitudes. *International Journal of Sports Physiology and Performance*.
- Bennell, K., Talbot, R., Wajswelner, H., Techovanich, W., Kelly, D., & Hall, A. (1998). Intra-rater and inter-rater reliability of a weight-bearing lunge measure of ankle dorsiflexion. *Australian Journal of Physiotherapy*, 44(3), 175-180.
- Bennell, K., Tully, E., & Harvey, N. (1999). Does the toe-touch test predict hamstring injury in Australian Rules footballers? *Australian Journal of Physiotherapy*, 45(2), 103-109.
- Birch, H. L. (2007). Tendon matrix composition and turnover in relation to functional requirements. *International Journal of Experimental Pathology*, 88(4), 241-248.
- Bittencourt, N., Meeuwisse, W., Mendonça, L., Nettel-Aguirre, A., Ocarino, J., & Fonseca, S. (2016). Complex systems approach for sports injuries: moving from risk factor identification to injury pattern recognition—narrative review and new concept. *British Journal of Sports Medicine*, bjsports-2015-095850.

- Blanch, P., & Gabbett, T. J. (2016). Has the athlete trained enough to return to play safely? The acute: chronic workload ratio permits clinicians to quantify a player's risk of subsequent injury. *British Journal of Sports Medicine*, *50*(8), 471-475. doi: 10.1136/bjsports-2015-095445
- Boesen, A. P., Dideriksen, K., Couppé, C., Magnusson, S., Schjerling, P., Boesen, M., . . . Langberg, H. (2013). Tendon and skeletal muscle matrix gene expression and functional responses to immobilisation and rehabilitation in young males: effect of growth hormone administration. *The Journal of physiology*, *591*(23), 6039-6052.
- Bohm, S., Mersmann, F., Marzilger, R., Schroll, A., & Arampatzis, A. (2015). Asymmetry of Achilles tendon mechanical and morphological properties between both legs. *Scandinavian Journal of Medicine and Science in Sports*, *25*(1), e124-e132.
- Borresen, J., & Lambert, M. I. (2008). Quantifying training load: a comparison of subjective and objective methods. *International Journal of Sports Physiology and Performance*, *3*(1), 16.
- Borresen, J., & Lambert, M. I. (2009). The Quantification of Training Load, the Training Response and the Effect on Performance. *Sports Medicine*, *39*(9), 779-779. doi: 10.2165/11317780-000000000-00000
- Bourdon, P. C., Cardinale, M., Murray, A., Gatin, P., Kellmann, M., Varley, M. C., . . . Gregson, W. (2017). Monitoring Athlete Training Loads: Consensus Statement. *International Journal of Sports Physiology and Performance*, *12*(Suppl 2), S2-161-S162-170.

- Boyd, L. J., Ball, K., & Aughey, R. J. (2013). Quantifying external load in Australian football matches and training using accelerometers. *International Journal of Sports Physiology and Performance*, 8(1), 44-51.
- Bradley, P. S., & Portas, M. D. (2007). The relationship between preseason range of motion and muscle strain injury in elite soccer players. *The Journal of Strength & Conditioning Research*, 21(4), 1155-1159.
- Bradley, P. S., Sheldon, W., Wooster, B., Olsen, P., Boanas, P., & Krstrup, P. (2009). High-intensity running in English FA Premier League soccer matches. *Journal of Sports Sciences*, 27(2), 159-168.
- Brooks, J. H., Fuller, C. W., Kemp, S. P., & Reddin, D. B. (2006). Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. *American Journal of Sports Medicine*, 34(8), 1297-1306. doi: 10.1177/0363546505286022
- Buchheit, M. (2015). Sensitivity of monthly heart rate and psychometric measures for monitoring physical performance in highly trained young handball players. *International Journal of Sports Medicine*, 36(05), 351-356.
- Buchheit, M. (2017). Applying the acute:chronic workload ratio in elite football: worth the effort? *British Journal of Sports Medicine*, 51(18), 1325-1327. doi: 10.1136/bjsports-2016-097017
- Buchheit, M., Racinais, S., Bilsborough, J., Bourdon, P., Voss, S., Hocking, J., . . . Coutts, A. (2013). Monitoring fitness, fatigue and running performance during a pre-season training camp in elite football players. *Journal of Science and Medicine in Sport*, 16(6), 550-555.

- Budgett, R., Newsholme, E., Lehmann, M., Sharp, C., Jones, D., Jones, T., . . . White, P. (2000). Redefining the overtraining syndrome as the unexplained underperformance syndrome. *British Journal of Sports Medicine, 34*(1), 67-68.
- Burgess, D., Naughton, G., & Norton, K. (2012). Quantifying the gap between under 18 and senior AFL football: 2003 and 2009. *International Journal of Sports Physiology and Performance, 7*(1), 53-58.
- Burkett, L. N. (1970). Causative factors in hamstring strains. *Medicine and Science in Sports, 2*(1), 39-42.
- Caldwell, B. P., & Peters, D. M. (2009). Seasonal variation in physiological fitness of a semiprofessional soccer team. *The Journal of Strength & Conditioning Research, 23*(5), 1370-1377.
- Carey, D. L., Blanch, P., Ong, K. L., Crossley, K. M., Crow, J., & Morris, M. E. (2017). Training loads and injury risk in Australian football-differing acute: chronic workload ratios influence match injury risk. *British Journal of Sports Medicine, 51*(16), 1215-1220. doi: 10.1136/bjsports-2016-096309
- Carey, D. L., Ong, K.-L., Whiteley, R., Crossley, K. M., Crow, J., & Morris, M. E. (2018). Predictive modelling of training loads and injury in Australian football. *International Journal of Computer Science in Sport, 17*(1), 49-66. doi: 10.2478/ijcss-2018-0002
- Casamichana, D., Castellano, J., Calleja-Gonzalez, J., San Román, J., & Castagna, C. (2013). Relationship between indicators of training load in soccer players. *Journal Of Strength And Conditioning Research / National*

- Strength & Conditioning Association*, 27(2), 369. doi: 10.1519/JSC.0b013e3182548af1
- Chamari, K., & Bahr, R. (2016). Training for elite sport performance: injury risk management also matters!
- Charlton, P. C., Ilott, D., Borgeaud, R., & Drew, M. K. (2017). Risky business: an example of what training load data can add to shared decision making in determining 'acceptable risk'. *Journal of Science and Medicine in Sport*, 20(6), 526-527.
- Clagg, S. E., Warnock, A., & Thomas, J. S. (2009). Kinetic analyses of maximal effort soccer kicks in female collegiate athletes. *Sports Biomechanics*, 8(2), 141-153.
- Clarsen, B., & Berge, H. M. (2016). Screening is dead. Long live screening! *British Journal of Sports Medicine*, 50(13), 769. doi: 10.1136/bjsports-2016-096475
- Colby, M. J., Dawson, B., Heasman, J., Rogalski, B., & Gabbett, T. J. (2014). Accelerometer and GPS-Derived Running Loads and Injury Risk in Elite Australian Footballers. *The Journal of Strength & Conditioning Research*, 28(8), 2244-2252. doi: 10.1519/jsc.0000000000000362
- Colby, M. J., Dawson, B., Heasman, J., Rogalski, B., Rosenberg, M., Lester, L., & Peeling, P. (2017). Preseason Workload Volume and High-Risk Periods for Noncontact Injury Across Multiple Australian Football League Seasons. *The Journal of Strength & Conditioning Research*, 31(7), 1821-1829.
- Colby, M. J., Dawson, B., Peeling, P., Heasman, J., Rogalski, B., Drew, M. K., . . . Lester, L. (2017). Multivariate modelling of subjective and objective

- monitoring data improve the detection of non-contact injury risk in elite Australian footballers. *Journal of Science and Medicine in Sport*. doi: 10.1016/j.jsams.2017.05.010
- Cook, J., Khan, K. M., Kiss, Z., Coleman, B., & Griffiths, L. (2001). Asymptomatic hypoechoic regions on patellar tendon ultrasound: A 4-year clinical and ultrasound followup of 46 tendons. *Scandinavian Journal of Medicine and Science in Sports*, 11(6), 321-327.
- Cook, J., Khan, K. M., & Purdam, C. (2002). Achilles tendinopathy. *Manual Therapy*, 7(3), 121-130.
- Cook, J., & Purdam, C. R. (2009). Is tendon pathology a continuum? A pathology model to explain the clinical presentation of load-induced tendinopathy. *British Journal of Sports Medicine*, 43(6), 409-416.
- Cook, J., Rio, E., Purdam, C., & Docking, S. (2016). Revisiting the continuum model of tendon pathology: what is its merit in clinical practice and research? *British Journal of Sports Medicine*, bjsports-2015-095422.
- Corlett, J. T. (1976). *A systems model of physical training and athletic performance*. Simon Fraser University. Theses (Dept. of Kinesiology).
- Cormack, S. J., Mooney, M. G., Morgan, W., & McGuigan, M. R. (2013). Influence of neuromuscular fatigue on accelerometer load in elite Australian football players. *International Journal of Sports Physiology and Performance*, 8(4), 373-378.
- Coupe, C., Kongsgaard, M., Aagaard, P., Hansen, P., Bojsen-Moller, J., Kjaer, M., & Magnusson, S. P. (2008). Habitual loading results in tendon

- hypertrophy and increased stiffness of the human patellar tendon. *Journal of Applied Physiology*, 105(3), 805-810.
- Couppé, C., Suetta, C., Kongsgaard, M., Justesen, L., Hvid, L., Aagaard, P., . . . Magnusson, S. P. (2012). The effects of immobilization on the mechanical properties of the patellar tendon in younger and older men. *Clinical Biomechanics*, 27(9), 949-954.
- Coutts, A. J., & Duffield, R. (2010). Validity and reliability of GPS devices for measuring movement demands of team sports. *Journal of Science and Medicine in Sport*, 13(1), 133-135.
- Coutts, A. J., & Reaburn, P. (2008). Monitoring changes in rugby league players' perceived stress and recovery during intensified training. *Perceptual and Motor Skills*, 106(3), 904-916.
- Creighton, D. W., Shrier, I., Shultz, R., Meeuwisse, W. H., & Matheson, G. O. (2010). Return-to-play in sport: a decision-based model. *Clinical Journal of Sport Medicine*, 20(5), 379-385. doi: 10.1097/JSM.0b013e3181f3c0fe
- Croisier, J.-L. (2004). Factors associated with recurrent hamstring injuries. *Sports Medicine*, 34(10), 681-695.
- Cross, M. J., Williams, S., Trewartha, G., Kemp, S. P., & Stokes, K. A. (2016). The influence of in-season training loads on injury risk in professional rugby union. *International Journal of Sports Physiology and Performance*, 11(3), 350-355.
- Crow, J. F., Pearce, A. J., Veale, J. P., VanderWesthuizen, D., Coburn, P. T., & Pizzari, T. (2010). Hip adductor muscle strength is reduced preceding and during the onset of groin pain in elite junior Australian football players.

Journal of Science and Medicine in Sport, 13(2), 202-204. doi:
10.1016/j.jsams.2009.03.007

Dauty, M., Potiron-Josse, M., & Rochcongar, P. (2003). Identification of previous hamstring muscle injury by isokinetic concentric and eccentric torque measurement in elite soccer player. *Isokinetics and Exercise Science*, 11(3), 139-144.

Dawson, B., Gow, S., Modra, S., Bishop, D., & Stewart, G. (2005). Effects of immediate post-game recovery procedures on muscle soreness, power and flexibility levels over the next 48 hours. *Journal of Science and Medicine in Sport*, 8(2), 210-221.

Dawson, B., Hopkinson, R., Appleby, B., Stewart, G., & Roberts, C. (2004). Player movement patterns and game activities in the Australian Football League. *Journal of Science and Medicine in Sport*, 7(3), 278-291.

De Boer, M. D., Selby, A., Atherton, P., Smith, K., Seynnes, O. R., Maganaris, C. N., . . . Rennie, M. J. (2007). The temporal responses of protein synthesis, gene expression and cell signalling in human quadriceps muscle and patellar tendon to disuse. *The Journal of physiology*, 585(1), 241-251.

Delahunt, E., Fitzpatrick, H., & Blake, C. (2017). Pre-season adductor squeeze test and HAGOS function sport and recreation subscale scores predict groin injury in Gaelic football players. *Physical Therapy in Sport* 23, 1-6.

Dennis, R. J., Finch, C. F., Elliott, B. C., & Farhart, P. J. (2008). The reliability of musculoskeletal screening tests used in cricket. *Physical Therapy in Sport* 9(1), 25-33.

- Dideriksen, K. (2014). Muscle and tendon connective tissue adaptation to unloading, exercise and NSAID. *Connective Tissue Research*, 55(2), 61-70.
- Docking, S. I. (2015). *The Characteristics of Tendon Pathology and Its Pathogenesis as Detected by Ultrasound Tissue Characterisation*. Monash University.
- Docking, S. I., & Cook, J. (2015). Pathological tendons maintain sufficient aligned fibrillar structure on ultrasound tissue characterization (UTC). *Scandinavian Journal of Medicine and Science in Sports*.
- Docking, S. I., Ooi, C. C., & Connell, D. (2015). Tendinopathy: is imaging telling us the entire story? *Journal of Orthopaedic and Sports Physical Therapy*, 45(11), 842-852.
- Docking, S. I., Rosengarten, S. D., & Cook, J. (2016). Achilles tendon structure improves on UTC imaging over a 5-month pre-season in elite Australian football players. *Scandinavian Journal of Medicine and Science in Sports*, 26(5), 557-563. doi: 10.1111/sms.12469
- Docking, S. I., Rosengarten, S. D., Daffy, J., & Cook, J. (2014). Structural integrity is decreased in both Achilles tendons in people with unilateral Achilles tendinopathy. *Journal of Science and Medicine in Sport*.
- Drew, M. K., Blanch, P., Purdam, C., & Gabbett, T. J. (2017). Yes, rolling averages are a good way to assess training load for injury prevention. Is there a better way? Probably, but we have not seen the evidence. *British Journal of Sports Medicine*, 51(7), 618-619.

- Drew, M. K., & Finch, C. F. (2016). The relationship between training load and injury, illness and soreness: a systematic and literature review. *Sports Medicine*, 46(6), 861-883.
- Duhig, S., Shield, A. J., Opar, D., Gabbett, T. J., Ferguson, C., & Williams, M. (2016). Effect of high-speed running on hamstring strain injury risk. *British Journal of Sports Medicine*, 50(24), 1536-1540.
- Ebert, T. R., Martin, D. T., McDonald, W., Victor, J., Plummer, J., & Withers, R. T. (2005). Power output during women's World Cup road cycle racing. *European Journal of Applied Physiology*, 95(5-6), 529-536.
- Ehrmann, F. E., Duncan, C. S., Sindhusake, D., Franzsen, W. N., & Greene, D. A. (2016). GPS and injury prevention in professional soccer. *The Journal of Strength & Conditioning Research*, 30(2), 360-367.
- Ekstrand, J. (2013). Keeping your top players on the pitch: the key to football medicine at a professional level: BMJ Publishing Group Ltd and British Association of Sport and Exercise Medicine.
- Elloumi, M., Makni, E., Moalla, W., Bouaziz, T., Tabka, Z., Lac, G., & Chamari, K. (2012). Monitoring Training Load and Fatigue in Rugby Sevens Players. *Asian Journal of Sports Medicine*, 3(3), 175-184.
- Engebretsen, A. H., Myklebust, G., Holme, I., Engebretsen, L., & Bahr, R. (2010). Intrinsic Risk Factors for Groin Injuries Among Male Soccer Players A Prospective Cohort Study. *The American Journal Of Sports Medicine*, 38(10), 2051-2057.
- Fanchini, M., Rampinini, E., Riggio, M., Coutts, A. J., Pecci, C., & McCall, A. (2018). Despite association, the acute: chronic work load ratio does not

- predict non-contact injury in elite footballers. *Science and Medicine in Football*, 2(2), 108-114.
- Finch, C. F., & Cook, J. (2014). Categorising sports injuries in epidemiological studies: the subsequent injury categorisation (SIC) model to address multiple, recurrent and exacerbation of injuries. *British Journal of Sports Medicine*, 48(17), 1276-1280. doi: 10.1136/bjsports-2012-091729
- Finch, C. F., Cook, J., Kunstler, B. E., Akram, M., & Orchard, J. (2017). Subsequent Injuries Are More Common Than Injury Recurrences: An Analysis of 1 Season of Prospectively Collected Injuries in Professional Australian Football. *The American Journal Of Sports Medicine*, 45(8), 1921-1927. doi: 10.1177/0363546517691943
- Fortington, L. V., Berry, J., Buttifant, D., Ullah, S., Diamantopoulou, K., & Finch, C. F. (2016). Shorter time to first injury in first year professional football players: a cross-club comparison in the Australian Football League. *Journal of Science and Medicine in Sport*, 19(1), 18-23.
- Foster, C. (1998). Monitoring training in athletes with reference to overtraining syndrome. *Medicine and Science in Sports and Exercise*, 30(7), 1164-1168. doi: 10.1097/00005768-199807000-00023
- Foster, C., Florhaug, J. A., Franklin, J., Gottschall, L., Hrovatin, L. A., Parker, S., . . . Dodge, C. (2001). A new approach to monitoring exercise training. *The Journal of Strength & Conditioning Research*, 15(1), 109-115.
- Foster, C., Hector, L. L., Welsh, R., Schragar, M., Green, M. A., & Snyder, A. C. (1995). Effects of specific versus cross-training on running performance.

- European Journal of Applied Physiology and Occupational Physiology*, 70(4), 367-372.
- Freckleton, G., & Pizzari, T. (2012). Risk factors for hamstring muscle strain injury in sport: a systematic review and meta-analysis. *British Journal of Sports Medicine*, bjsports-2011-090664.
- Fredberg, U., & Bolvig, L. (2002). Significance of Ultrasonographically Detected Asymptomatic Tendinosis in the Patellar and Achilles Tendons of Elite Soccer Players A Longitudinal Study. *The American Journal Of Sports Medicine*, 30(4), 488-491.
- Fredberg, U., Bolvig, L., & Andersen, N. T. (2008). Prophylactic Training in Asymptomatic Soccer Players With Ultrasonographic Abnormalities in Achilles and Patellar Tendons The Danish Super League Study. *The American Journal Of Sports Medicine*, 36(3), 451-460.
- Fry, R. W., Morton, A. R., & Keast, D. (1991). Overtraining in athletes. *Sports Medicine*, 12(1), 32-65.
- Fuller, C. W., Ekstrand, J., Junge, A., Andersen, T. E., Bahr, R., Dvorak, J., . . . Meeuwisse, W. H. (2006). Consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries. *Scandinavian Journal of Medicine and Science in Sports*, 16(2), 83-92.
- Fulton, J., Wright, K., Kelly, M., Zebrosky, B., Zanis, M., Drvol, C., & Butler, R. (2014). Injury risk is altered by previous injury: a systematic review of the literature and presentation of causative neuromuscular factors. *International Journal of Sports Physical Therapy*, 9(5), 583.

- Gabbe, B., Bennell, K., & Finch, C. (2006). Why are older Australian football players at greater risk of hamstring injury? *Journal of Science and Medicine in Sport*, 9(4), 327-333. doi: 10.1016/j.jsams.2006.01.004
- Gabbe, B., Bennell, K., Finch, C., Wajswelner, H., & Orchard, J. (2006). Predictors of hamstring injury at the elite level of Australian football. *Scandinavian Journal of Medicine and Science in Sports*, 16(1), 7-13.
- Gabbe, B., Bennell, K., Wajswelner, H., & Finch, C. (2004). Reliability of common lower extremity musculoskeletal screening tests. *Physical Therapy in Sport* 5(2), 90-97.
- Gabbe, B., Finch, C., Bennell, K., & Wajswelner, H. (2003). How valid is a self reported 12 month sports injury history? *British Journal of Sports Medicine*, 37(6), 545-547.
- Gabbett, H. T., Windt, J., & Gabbett, T. J. (2016). Cost-benefit analysis underlies training decisions in elite sport. *British Journal of Sports Medicine*, 50(21), 1291-1292. doi: 10.1136/bjsports-2016-096079
- Gabbett, T. J. (2010). The development and application of an injury prediction model for noncontact, soft-tissue injuries in elite collision sport athletes. *The Journal of Strength & Conditioning Research*, 24(10), 2593-2603. doi: 10.1519/JSC.0b013e3181f19da4
- Gabbett, T. J. (2016). The training—injury prevention paradox: should athletes be training smarter and harder? *British Journal of Sports Medicine*, 50(5), 273-280. doi: 10.1136/bjsports-2015-095788

- Gabbett, T. J., & Jenkins, D. G. (2011). Relationship between training load and injury in professional rugby league players. *Journal of Science and Medicine in Sport, 14*(3), 204-209.
- Gabbett, T. J., Nassis, G. P., Oetter, E., Pretorius, J., Johnston, N., Medina, D., . . . Ryan, A. (2017). The athlete monitoring cycle: a practical guide to interpreting and applying training monitoring data. *British Journal of Sports Medicine, 51*(20), 1451-1452. doi: 10.1136/bjsports-2016-097298
- Gabbett, T. J., & Ullah, S. (2012). Relationship between running loads and soft-tissue injury in elite team sport athletes. *Journal Of Strength And Conditioning Research / National Strength & Conditioning Association, 26*(4), 953-960. doi: 10.1519/JSC.0b013e3182302023
- Gallo, T. F., Cormack, S. J., Gabbett, T. J., & Lorenzen, C. H. (2017). Self-reported wellness profiles of professional Australian football players during the competition phase of the season. *The Journal of Strength & Conditioning Research, 31*(2), 495-502.
- Gamble, P. (2006). Periodization of training for team sports athletes. *Strength and Conditioning Journal, 28*(5), 56.
- Garrett Jr, W., Safran, M. R., Seaber, A. V., Glisson, R. R., & Ribbeck, B. M. (1987). Biomechanical comparison of stimulated and nonstimulated skeletal muscle pulled to failure. *The American Journal Of Sports Medicine, 15*(5), 448-454.
- Garrick, J. G. (2004). Preparticipation orthopedic screening evaluation. *Clinical Journal of Sport Medicine, 14*(3), 123-126.

- Gastin, P. B., McLean, O., Spittle, M., & Breed, R. V. (2013). Quantification of tackling demands in professional Australian football using integrated wearable athlete tracking technology. *Journal of Science and Medicine in Sport*, 16(6), 589-593.
- Gastin, P. B., Meyer, D., Huntsman, E., & Cook, J. (2014). Low body mass and aerobic running fitness increase injury risk in elite Australian football. *International Journal of Sports Physiology and Performance*, 10(4), 458-463.
- Gastin, P. B., Meyer, D., & Robinson, D. (2013). Perceptions of wellness to monitor adaptive responses to training and competition in elite Australian football. *Journal of Strength and Conditioning Research*, 27(9), 2518-2526.
- Giombini, A., Dragoni, S., Di Cesare, A., Di Cesare, M., Del Buono, A., & Maffulli, N. (2013). Asymptomatic Achilles, patellar, and quadriceps tendinopathy: a longitudinal clinical and ultrasonographic study in elite fencers. *Scandinavian Journal of Medicine and Science in Sports*, 23(3), 311-316.
- Gleim, G. W., & McHugh, M. P. (1997). Flexibility and its effects on sports injury and performance. *Sports Medicine*, 24(5), 289-299.
- Hägglund, M., & Waldén, M. (2012). Epidemiology of football injuries. *Dansk SportsMedicin*, 4(16), 10-12.
- Hägglund, M., Waldén, M., & Ekstrand, J. (2006). Previous injury as a risk factor for injury in elite football: a prospective study over two consecutive seasons. *British Journal of Sports Medicine*, 40(9), 767-772. doi: 10.1136/bjism.2006.026609

- Hägglund, M., Waldén, M., & Ekstrand, J. (2013). Risk Factors for Lower Extremity Muscle Injury in Professional Soccer: The UEFA Injury Study. *The American Journal Of Sports Medicine*, 41(2), 327-335. doi: 10.1177/0363546512470634
- Hagglund, M., Walden, M., Magnusson, H., Kristenson, K., Bengtsson, H., & Ekstrand, J. (2013). Injuries affect team performance negatively in professional football: an 11-year follow-up of the UEFA Champions League injury study. *British Journal of Sports Medicine*, 47(12), 738-742. doi: 10.1136/bjsports-2013-092215
- Halson, S. L. (2014). Monitoring training load to understand fatigue in athletes. *Sports Medicine*, 44(2), 139-147.
- Halson, S. L., & Jeukendrup, A. E. (2004). Does overtraining exist? *Sports Medicine*, 34(14), 967-981.
- Hamilton, G. M., Meeuwisse, W. H., Emery, C. A., Steele, R. J., & Shrier, I. (2011). Past Injury as a Risk Factor: An Illustrative Example Where Appearances Are Deceiving. *American Journal of Epidemiology*, 173(8), 941-948. doi: 10.1093/aje/kwq461
- Hawley, J. A. (2002). Adaptations of skeletal muscle to prolonged, intense endurance training. *Clinical and Experimental Pharmacology and Physiology*, 29(3), 218-222.
- Hébert-Losier, K., Platt, S., & Hopkins, W. G. (2015). Sources of Variability in Performance Times at the World Orienteering Championships. *Medicine and Science in Sports and Exercise*, 47(7), 1523-1530.

- Heinemeier, K., & Kjaer, M. (2011). In vivo investigation of tendon responses to mechanical loading. *Journal of Musculoskeletal & Neuronal Interactions*, 11(2), 115-123.
- Henderson, G., Barnes, C. A., & Portas, M. D. (2010). Factors associated with increased propensity for hamstring injury in English Premier League soccer players. *Journal of Science and Medicine in Sport*, 13(4), 397-402.
- Hernán, M. A. (2010). The hazards of hazard ratios. *Epidemiology (Cambridge, Mass.)*, 21(1), 13.
- Hewett, T. E. (2017). Prediction of Future Injury in Sport: Primary and Secondary Anterior Cruciate Ligament Injury Risk and Return to Sport as a Model. *Journal of Orthopaedic and Sports Physical Therapy*, 47(4), 228-231.
- Hickey, J., Shield, A. J., Williams, M. D., & Opar, D. A. (2013). The financial cost of hamstring strain injuries in the Australian Football League. *British Journal of Sports Medicine*, bjsports-2013-092884.
- Hopkins, D. R., & Hoeger, W. W. (1992). A Comparison of the Sit-and-Reach Test and the Modified Sit-and-Reach Test in the Measurement of Flexibility for Males. *The Journal of Strength & Conditioning Research*, 6(1), 7-10.
- Hopkins, W. G. (1991). Quantification of training in competitive sports. Methods and applications. *Sports medicine (Auckland, NZ)*, 12(3), 161-183.
- Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine*, 30(1), 1-15.
- Hopkins, W. G. (2006a). Analysis of a post-only crossover trial, with adjustment for a predictor. *Sportscience*, 10, 46-50.

- Hopkins, W. G. (2006c). Estimating sample size for magnitude-based inferences. *Sportscience*, 10, 63-70.
- Hopkins, W. G. (2010). Linear models and effect magnitudes for research, clinical and practical applications. *Sportscience*, 14(1), 49-57.
- Hopkins, W. G. (2015). Individual responses made easy. *Journal of Applied Physiology*, 118, 1444-1446.
- Hopkins, W. G., & Batterham, A. M. (2016). Error rates, decisive outcomes and publication bias with several inferential methods. *Sports Medicine*, 46(10), 1563-1573.
- Hopkins, W. G., Batterham, A. M., Pyne, D. B., & Impellizzeri, F. M. (2011). Misplaced decimal places. *Scandinavian Journal of Medicine and Science in Sports*, 21(6), 867-868. doi: 10.1111/j.1600-0838.2011.01393.x
- Hopkins, W. G., Marshall, S., Batterham, A., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, 41(1), 3-13.
- Hopkins, W. G., Marshall, S. W., Quarrie, K. L., & Hume, P. A. (2007). Risk factors and risk statistics for sports injuries. *Clinical Journal of Sport Medicine*, 17(3), 208-210.
- Howe, S. T., Aughey, R. J., Hopkins, W. G., Stewart, A. M., & Cavanagh, B. P. (2017). *Quantifying important differences in athlete movement during collision-based team sports: Accelerometers outperform Global Positioning Systems*. Paper presented at the Inertial Sensors and Systems (INERTIAL), 2017 IEEE International Symposium on.

- Hrysomallis, C. (2013). Injury incidence, risk factors and prevention in Australian rules football. *Sports Medicine (Auckland, N.Z.)*, 43(5), 339-354. doi: 10.1007/s40279-013-0034-0
- Hulin, B. T., Gabbett, T. J., Blanch, P., Chapman, P., Bailey, D., & Orchard, J. W. (2014). Spikes in acute workload are associated with increased injury risk in elite cricket fast bowlers. *British Journal of Sports Medicine*, 48(8), 708-712. doi: 10.1136/bjsports-2013-092524
- Hulin, B. T., Gabbett, T. J., Caputi, P., Lawson, D. W., & Sampson, J. A. (2016). Low chronic workload and the acute:chronic workload ratio are more predictive of injury than between-match recovery time: a two-season prospective cohort study in elite rugby league players. *British Journal of Sports Medicine*, 50(16), 1008-1012. doi: 10.1136/bjsports-2015-095364
- Hulin, B. T., Gabbett, T. J., Lawson, D. W., Caputi, P., & Sampson, J. A. (2016). The acute: chronic workload ratio predicts injury: high chronic workload may decrease injury risk in elite rugby league players. *British Journal of Sports Medicine*, 50(4), 231-236. doi: 10.1136/bjsports-2015-094817
- Hulme, A., & Finch, C. F. (2015). From monocausality to systems thinking: a complementary and alternative conceptual approach for better understanding the development and prevention of sports injury. *Injury epidemiology*, 2(1), 31.
- Hunter, J. S. (1986). The exponentially weighted moving average. *J. Quality Technol.*, 18(4), 203-210.
- Impellizzeri, F. M., Rampinini, E., Coutts, A. J., Sassi, A., & Marcora, S. M. (2004). Use of RPE-based training load in soccer. *Medicine and Science in Sports*

and Exercise, 36(6), 1042-1047. doi:
10.1249/01.MSS.0000128199.23901.2F

Impellizzeri, F. M., Rampinini, E., & Marcora, S. M. (2005). Physiological assessment of aerobic training in soccer. *Journal of Sports Sciences*, 23(6), 583-592.

Jennings, D., Cormack, S., Coutts, A., Boyd, L., & Aughey, R. J. (2010). The validity and reliability of GPS units for measuring distance in team sport specific running patterns. *International Journal of Sports Physiology and Performance*, 5(3), 328.

Jeukendrup, A., & Diemen, A. V. (1998). Heart rate monitoring during training and competition in cyclists. *Journal of Sports Sciences*, 16(sup1), 91-99.

Johnston, R. D., Gibson, N. V., Twist, C., Gabbett, T. J., MacNay, S. A., & MacFarlane, N. G. (2013). Physiological responses to an intensified period of rugby league competition. *The Journal of Strength & Conditioning Research*, 27(3), 643-654.

Józsa, L., Bálint, J. B., Réffy, A., & Demel, Z. (1979). Histochemical and ultrastructural study of adult human tendon. *Acta Histochemica*, 65(2), 250-257.

Jozsa, L., Kannus, P., Balint, J. B., & Reffy, A. (1991). Three-dimensional ultrastructure of human tendons. *Acta Anatomica*, 142(4), 306-312.

Józsa, L., Lehto, M., Kvist, M., Bálint, J. B., & Reffy, A. (1989). Alterations in dry mass content of collagen fibers in degenerative tendinopathy and tendon-rupture. *Matrix*, 9(2), 140-146.

- Józsa, L., Réffy, A., & Bálint, J. B. (1984). Polarization and electron microscopic studies on the collagen of intact and ruptured human tendons. *Acta Histochemica*, 74(2), 209-215.
- Kannus, P. (2000). Structure of the tendon connective tissue. *Scandinavian Journal of Medicine and Science in Sports*, 10(6), 312-320.
- Kannus, P., & Jozsa, L. (1991). Histopathological changes preceding spontaneous rupture of a tendon. A controlled study of 891 patients. *Journal of Bone and Joint Surgery (American Volume)*, 73(10), 1507-1525.
- Kellmann, M. (2010). Preventing overtraining in athletes in high-intensity sports and stress/recovery monitoring. *Scandinavian Journal of Medicine and Science in Sports*, 20(s2), 95-102.
- Kellmann, M., & Kallus, K. W. (2001). *Recovery-stress questionnaire for athletes: User manual* (Vol. 1): Human Kinetics.
- Kelly, V. G., & Coutts, A. J. (2007). Planning and monitoring training loads during the competition phase in team sports. *Strength and Conditioning Journal*, 29(4), 32.
- Killen, N. M., Gabbett, T. J., & Jenkins, D. G. (2010). Training loads and incidence of injury during the preseason in professional rugby league players. *Journal Of Strength And Conditioning Research / National Strength & Conditioning Association*, 24(8), 2079-2084. doi: 10.1519/JSC.0b013e3181ddaff
- King, D. A., Gabbett, T. J., Gissane, C., & Hodgson, L. (2009). Epidemiological studies of injuries in rugby league: Suggestions for definitions, data

- collection and reporting methods. *Journal of Science and Medicine in Sport*, 12(1), 12-19. doi: <http://dx.doi.org/10.1016/j.jsams.2007.12.001>
- Kjaer, M. (2004). Role of extracellular matrix in adaptation of tendon and skeletal muscle to mechanical loading. *Physiological Reviews*, 84(2), 649-698.
- Knowles, S. B., Marshall, S. W., & Guskiewicz, K. M. (2006). Issues in estimating risks and rates in sports injury research. *Journal of Athletic Training*, 41(2), 207-215.
- Kongsgaard, M., Aagaard, P., Kjaer, M., & Magnusson, S. (2005). Structural Achilles tendon properties in athletes subjected to different exercise modes and in Achilles tendon rupture patients. *Journal of Applied Physiology*, 99(5), 1965-1971.
- Kongsgaard, M., Qvortrup, K., Larsen, J., Aagaard, P., Doessing, S., Hansen, P., . . . Magnusson, S. P. (2010). Fibril morphology and tendon mechanical properties in patellar tendinopathy effects of heavy slow resistance training. *The American Journal Of Sports Medicine*, 38(4), 749-756.
- Kongsgaard, M., Reitelseder, S., Pedersen, T. G., Holm, L., Aagaard, P., Kjær, M., & Magnusson, S. (2007). Region specific patellar tendon hypertrophy in humans following resistance training. *Acta physiologica*, 191(2), 111-121.
- Kraushaar, B. S., & Nirschl, R. P. (1999). Tendinosis of the elbow (tennis elbow): clinical features and findings of histological, immunohistochemical, and electron microscopy studies. *Journal of Bone and Joint Surgery*, 81(2), 259.

- Kreider, R. B., Fry, A. C., & O'Toole, M. L. (1998). *Overtraining in sport*. Champaign, IL, US: Human Kinetics.
- Kubo, K., Akima, H., Ushiyama, J., Tabata, I., Fukuoka, H., Kanehisa, H., & Fukunaga, T. (2004). Effects of 20 days of bed rest on the viscoelastic properties of tendon structures in lower limb muscles. *British Journal of Sports Medicine*, *38*(3), 324-330.
- Kubo, K., Ikebukuro, T., Maki, A., Yata, H., & Tsunoda, N. (2012). Time course of changes in the human Achilles tendon properties and metabolism during training and detraining in vivo. *European Journal of Applied Physiology*, *112*(7), 2679-2691. doi: 10.1007/s00421-011-2248-x
- Kubo, K., Ikebukuro, T., Yaeshima, K., Yata, H., Tsunoda, N., & Kanehisa, H. (2009). Effects of static and dynamic training on the stiffness and blood volume of tendon in vivo. *Journal of Applied Physiology*, *106*(2), 412-417.
- Kubo, K., Kanehisa, H., & Fukunaga, T. (2002). Effects of resistance and stretching training programmes on the viscoelastic properties of human tendon structures in vivo. *The Journal of physiology*, *538*(1), 219-226.
- Kubo, K., Kanehisa, H., Kawakami, Y., & Fukunaga, T. (2000). Elastic properties of muscle-tendon complex in long-distance runners. *European Journal of Applied Physiology*, *81*(3), 181-187.
- Kumar, S. (2001). Theories of musculoskeletal injury causation. *Ergonomics*, *44*(1), 17-47.
- Langberg, H., Rosendal, L., & Kjær, M. (2001). Training-induced changes in peritendinous type I collagen turnover determined by microdialysis in humans. *The Journal of physiology*, *534*(1), 297-302.

- Lazarus, B. H., Stewart, A. M., White, K. M., Rowell, A. E., Esmaeili, A., Hopkins, W. G., & Aughey, R. J. (2017). Proposal of a global training load measure predicting match performance in an elite team sport. *Frontiers in Physiology*, 8, 930. doi: 10.3389/fphys.2017.00930
- Lee, M., Reid, S. L., Elliott, B. C., & Lloyd, D. G. (2009). Running biomechanics and lower limb strength associated with prior hamstring injury. *Medicine and Science in Sports and Exercise*, 41(10), 1942-1951.
- Liu, Y., Sun, Y., Zhu, W., & Yu, J. (2017). The late swing and early stance of sprinting are most hazardous for hamstring injuries. *Journal of Sport and Health Science*.
- Lolli, L., Batterham, A. M., Hawkins, R., Kelly, D. M., Strudwick, A. J., Thorpe, R., . . . Atkinson, G. (2017). Mathematical coupling causes spurious correlation within the conventional acute-to-chronic workload ratio calculations. *British Journal of Sports Medicine*. doi: 10.1136/bjsports-2017-098110
- Maffey, L., & Emery, C. (2006). Physiotherapist delivered preparticipation examination: rationale and evidence. *North American journal of sports physical therapy: NAJSPT*, 1(4), 176.
- Maffey, L., & Emery, C. (2007). What are the Risk Factors for Groin Strain Injury in Sport?: A Systematic Review of the Literature. *Sports Medicine*, 37(10), 881-894. doi: 10.2165/00007256-200737100-00004
- Maffulli, N. (1998). Overuse tendon conditions: time to change a confusing terminology. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 14(8), 840-843.

- Maffulli, N. (1999). Current concepts review-Rupture of the Achilles tendon. *Journal of Bone and Joint Surgery (American Volume)*, 81(7), 1019-1036.
- Maganaris, C. N., Narici, M. V., Almekinders, L. C., & Maffulli, N. (2004). Biomechanics and Pathophysiology of Overuse Tendon Injuries. *Sports Medicine*, 34(14), 1005-1017. doi: 10.2165/00007256-200434140-00005
- Magnusson, S., Hansen, P., Aagaard, P., Brønd, J., Dyhre-Poulsen, P., Bojsen-Møller, J., & Kjaer, M. (2003). Differential strain patterns of the human gastrocnemius aponeurosis and free tendon, in vivo. *Acta Physiologica Scandinavica*, 177(2), 185-195.
- Malaviya, P., Bultler, D., Boivin, G., Smith, F., Barry, F., Murphy, J., & Vogel, K. (2000). An in vivo model for load-modulated remodeling in the rabbit flexor tendon. *Journal of Orthopaedic Research*, 18(1), 116-125.
- Malliaras, P., & Cook, J. (2006). Patellar tendons with normal imaging and pain: change in imaging and pain status over a volleyball season. *Clinical Journal of Sport Medicine*, 16(5), 388-391.
- Malliaras, P., Cook, J., Ptasznik, R., & Thomas, S. (2006). Prospective study of change in patellar tendon abnormality on imaging and pain over a volleyball season. *British Journal of Sports Medicine*, 40(3), 272-274.
- Malliaras, P., Hogan, A., Nawrocki, A., Crossley, K., & Schache, A. (2009). Hip flexibility and strength measures: reliability and association with athletic groin pain. *British Journal of Sports Medicine*, 43(10), 739-744.
- Malliaras, P., Kamal, B., Nowell, A., Farley, T., Dhamu, H., Simpson, V., . . . Reeves, N. D. (2013). Patellar tendon adaptation in relation to load-

- intensity and contraction type. *Journal of Biomechanics*, 46(11), 1893-1899.
- Malliaras, P., Purdam, C., Maffulli, N., & Cook, J. (2010). Temporal sequence of greyscale ultrasound changes and their relationship with neovascularity and pain in the patellar tendon. *British Journal of Sports Medicine*, 44(13), 944-947.
- Malone, S., Owen, A., Newton, M., Mendes, B., Collins, K. D., & Gabbett, T. J. (2017). The acute: chronic workload ratio in relation to injury risk in professional soccer. *Journal of Science and Medicine in Sport*, 20(6), 561-565.
- Maniar, N., Shield, A. J., Williams, M. D., Timmins, R. G., & Opar, D. A. (2016). Hamstring strength and flexibility after hamstring strain injury: a systematic review and meta-analysis. *British Journal of Sports Medicine*, 50(15), 909-920. doi: 10.1136/bjsports-2015-095311
- Manire, J. T., Kipp, R., Spencer, J., & Swank, A. M. (2010). Diurnal variation of hamstring and lumbar flexibility. *The Journal of Strength & Conditioning Research*, 24(6), 1464-1471.
- Martinoli, C., Derchi, L. E., Pastorino, C., Bertolotto, M., & Silvestri, E. (1993). Analysis of echotexture of tendons with US. *Radiology*, 186(3), 839-843.
- McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011). Markers of postmatch fatigue in professional rugby league players. *The Journal of Strength & Conditioning Research*, 25(4), 1030-1039.
- McManus, A., Stevenson, M., Finch, C. F., Elliott, B., Hamer, P., Lower, A., & Bulsara, M. (2004). Incidence and risk factors for injury in non-elite

- Australian Football. *Journal of Science and Medicine in Sport*, 7(3), 384-391. doi: 10.1016/S1440-2440(04)80033-1
- Meeusen, R., Duclos, M., Foster, C., Fry, A., Gleeson, M., Nieman, D., . . . Urhausen, A. (2013). Prevention, diagnosis, and treatment of the overtraining syndrome: joint consensus statement of the European College of Sport Science and the American College of Sports Medicine. *Medicine and Science in Sports and Exercise*, 45(1), 186-205.
- Meeusen, R., Nederhof, E., Buyse, L., Roelands, B., De Schutter, G., & Piacentini, M. F. (2010). Diagnosing overtraining in athletes using the two-bout exercise protocol. *British Journal of Sports Medicine*, 44(9), 642-648.
- Meeuwisse, W. H. (1994a). Assessing causation in sport injury: a multifactorial model. *Clinical Journal of Sport Medicine*, 4(3), 166-170.
- Meeuwisse, W. H. (1994g). Athletic injury etiology: distinguishing between interaction and confounding. *Clinical Journal of Sport Medicine*, 4(3), 171-175.
- Meeuwisse, W. H., Tyreman, H., Hagel, B., & Emery, C. (2007). A dynamic model of etiology in sport injury: the recursive nature of risk and causation. *Clinical Journal of Sport Medicine*, 17(3), 215-219.
- Menaspa, P. (2017a). Are rolling averages a good way to assess training load for injury prevention? *British Journal of Sports Medicine*, 51(7), 618-619.
- Menaspa, P. (2017h). Building evidence with flawed data? The importance of analysing valid data. *British Journal of Sports Medicine*, 51(15), 1173. doi: 10.1136/bjsports-2016-097029

- Milanez, V. F., Ramos, S. P., Okuno, N. M., Boullosa, D. A., & Nakamura, F. Y. (2014). Evidence of a Non-Linear Dose-Response Relationship between Training Load and Stress Markers in Elite Female Futsal Players. *Journal of Sports Science & Medicine*, 13(1), 22-29.
- Miller, B. F., Hansen, M., Olesen, J. L., Schwarz, P., Babraj, J. A., Smith, K., . . . Kjaer, M. (2007). Tendon collagen synthesis at rest and after exercise in women. *Journal of Applied Physiology*, 102(2), 541-546.
- Moreira, A., Bilsborough, J. C., Sullivan, C. J., Cianciosi, M., Aoki, M. S., & Coutts, A. J. (2015). Training periodization of professional Australian Football players during an entire Australian Football League season. *International Journal of Sports Physiology and Performance*, 10(5), 566-571.
- Morgan, W., Poulos, N., Wallace, J., Bode, M., & Buchheit, M. (2014). Load and fatigue monitoring in Australian football: A practical example. *Journal of Australian Strength & Conditioning*, 22(5), 149-152.
- Morgans, R., Orme, P., Anderson, L., & Drust, B. (2014). Principles and practices of training for soccer. *Journal of Sport and Health Science*, 3(4), 251-257.
- Movin, T., Kristoffersen-Wiberg, M., Shalabi, A., Gad, A., Aspelin, P., & Rolf, C. (1998). Intratendinous alterations as imaged by ultrasound and contrast medium-enhanced magnetic resonance in chronic achillodynia. *Foot and Ankle International*, 19(5), 311-317.
- Mujika, I., & Padilla, S. (2000). Detraining: loss of training-induced physiological and performance adaptations. Part I. *Sports Medicine*, 30(2), 79-87.
- Murray, N. B., Gabbett, T. J., Townshend, A., Hulin, B. T., & McLellan, C. (2017). Individual and combined effects of acute and chronic running loads on

- injury risk in elite Australian footballers. *Scandinavian Journal of Medicine and Science in Sports*, 27(9), 990-998.
- Murray, N. B., Gabbett, T. J., & Townshend, A. D. (2017). Relationship between pre-season training load and in-season availability in elite Australian football players. *International Journal of Sports Physiology and Performance*, 12(6), 749-755.
- Murray, N. B., Gabbett, T. J., Townshend, A. D., & Blanch, P. (2017). Calculating acute: chronic workload ratios using exponentially weighted moving averages provides a more sensitive indicator of injury likelihood than rolling averages. *British Journal of Sports Medicine*, 51(9), 749-754.
- Nehrer, S., Breitenseher, M., Brodner, W., Kainberger, F., Fellingner, E., Engel, A., & Imhof, H. (1997). Clinical and sonographic evaluation of the risk of rupture in the Achilles tendon. *Archives of Orthopaedic and Trauma Surgery*, 116(1-2), 14-18.
- Nikolaou, P. K., Macdonald, B. L., Glisson, R. R., Seaber, A. V., & Garrett Jr, W. (1987). Biomechanical and histological evaluation of muscle after controlled strain injury. *The American Journal Of Sports Medicine*, 15(1), 9-14.
- O'Brien, M. (1997). Structure and metabolism of tendons. *Scandinavian Journal of Medicine and Science in Sports*, 7(2), 55-61.
- Öhberg, L., Lorentzon, R., & Alfredson, H. (2004). Eccentric training in patients with chronic Achilles tendinosis: normalised tendon structure and decreased thickness at follow up. *British Journal of Sports Medicine*, 38(1), 8-11.

- Opar, D. A., Williams, M. D., Timmins, R. G., Hickey, J., Duhig, S. J., & Shield, A. J. (2015). Eccentric hamstring strength and hamstring injury risk in Australian footballers. *Medicine and Science in Sports and Exercise*, 47(4), 857-865. doi: 10.1249/mss.0000000000000465
- Orchard, J. (2001). Intrinsic and extrinsic risk factors for muscle strains in Australian football. *American Journal of Sports Medicine*, 29(3), 300-303. doi: 10.1177/03635465010290030801
- Orchard, J., & Best, T. M. (2002). The Management of Muscle Strain Injuries: An Early Return Versus the Risk of Recurrence. *Clinical Journal of Sport Medicine*, 12(1), 3-5.
- Orchard, J., Best, T. M., & Verrall, G. M. (2005). Return to play following muscle strains. *Clinical Journal of Sport Medicine*, 15(6), 436-441. doi: 10.1097/01.jsm.0000188206.54984.65
- Orchard, J., Kountouris, A., & Sims, K. (2017). Risk factors for hamstring injuries in Australian male professional cricket players. *Journal of Sport and Health Science*, 6(3), 271-274. doi: 10.1016/j.jshs.2017.05.004
- Orchard, J., & Seward, H. (2009). Comparing AFL Injury Surveillance to other codes. *Sport Health*, 27(2), 38.
- Orchard, J., Seward, H., McGivern, J., & Hood, S. (2001). Intrinsic and extrinsic risk factors for anterior cruciate ligament injury in Australian footballers. *The American Journal Of Sports Medicine*, 29(2), 196-200. doi: 10.1177/03635465010290021301
- Orchard, J., Seward, H., & Orchard, J. (2013a). 2012 AFL Injury Report.

- Orchard, J., Seward, H., & Orchard, J. J. (2013b). Results of 2 decades of injury surveillance and public release of data in the Australian Football League. *The American Journal Of Sports Medicine*, 0363546513476270.
- Ottani, V., Raspanti, M., & Ruggeri, A. (2001). Collagen structure and functional implications. *Micron*, 32(3), 251-260.
- Owen, A. L., Forsyth, J. J., Wong, D. P., Dellal, A., Connelly, S. P., & Chamari, K. (2015). Heart rate-based training intensity and its impact on injury incidence among elite-level professional soccer players. *The Journal of Strength & Conditioning Research*, 29(6), 1705-1712.
- Pang, B. S., & Ying, M. (2006). Sonographic measurement of Achilles tendons in asymptomatic subjects variation with age, body height, and dominance of ankle. *Journal of Ultrasound in Medicine*, 25(10), 1291-1296.
- Paul, D. J., Nassis, G. P., Whiteley, R., Marques, J. B., Kenneally, D., & Chalabi, H. (2014). Acute responses of soccer match play on hip strength and flexibility measures: potential measure of injury risk. *Journal of Sports Sciences*, 32(13), 1318-1323.
- Pepe, M. S., Janes, H., Longton, G., Leisenring, W., & Newcomb, P. (2004). Limitations of the odds ratio in gauging the performance of a diagnostic, prognostic, or screening marker. *American Journal of Epidemiology*, 159(9), 882-890.
- Pfirschmann, C. W., Jost, B., Pirkl, C., Aitzetmüller, G., & Lajtai, G. (2008). Quadriceps tendinosis and patellar tendinosis in professional beach volleyball players: sonographic findings in correlation with clinical symptoms. *European Radiology*, 18(8), 1703-1709.

- Picerno, P. (2017). The Hamstrings-Injury-Mechanism Debate: Are We Close to an Agreement? *Journal Of Sport Rehabilitation, 26*(2), 120-121.
- Piggott, B., Newton, M. J., & McGuigan, M. R. (2009). The relationship between training load and incidence of injury and illness over a pre-season at an Australian football league club. *Journal of Australian Strength and Conditioning, 17*(3).
- Pizzari, T., Coburn, P. T., & Crow, J. F. (2008). Prevention and management of osteitis pubis in the Australian Football League: A qualitative analysis. *Physical Therapy in Sport 9*(3), 117-125. doi: 10.1016/j.ptsp.2008.06.002
- Prior, M., Guerin, M., & Grimmer, K. (2009). An evidence-based approach to hamstring strain injury: a systematic review of the literature. *Sports Health, 1*(2), 154-164.
- Putlur, P., Foster, C., Miskowski, J. A., Kane, M. K., Burton, S. E., Scheett, T. P., & McGuigan, M. R. (2004). Alteration of Immune Function in Women Collegiate Soccer Players and College Students. *Journal of Sports Science & Medicine, 3*(4), 234-243.
- Pyne, D. B., Gleeson, M., McDonald, W. A., Clancy, R. L., Perry Jr, C., & Fricker, P. A. (2000). Training Strategies to Maintain Immunocompetence in Athletes. *International Journal of Sports Medicine, 21*(Sup. 1), 51-60. doi: 10.1055/s-2000-1452
- Raglin, J., & Morgan, W. (1994). Development of a scale for use in monitoring training-induced distress in athletes. *International Journal of Sports Medicine, 15*(02), 84-88.

- Rampinini, E., Coutts, A. J., Castagna, C., Sassi, R., & Impellizzeri, F. (2007). Variation in top level soccer match performance. *International Journal of Sports Medicine*, 28(12), 1018-1024.
- Rasmussen, O. (2000). Sonography of tendons. *Scandinavian Journal of Medicine and Science in Sports*, 10(6), 360-364.
- Reilly, T., & Thomas, V. (1976). A motion analysis of work-rate in different positional roles in professional football match-play. *Journal of human movement studies*, 2(2), 87-97.
- Rio, E., Moseley, L., Purdam, C., Samiric, T., Kidgell, D., Pearce, A. J., . . . Cook, J. (2014). The pain of tendinopathy: physiological or pathophysiological? *Sports Medicine*, 44(1), 9-23.
- Ritchie, D., Hopkins, W. G., Buchheit, M., Cordy, J., & Bartlett, J. (2015). Quantification of Training and Competition Load Across a Season in an Elite Australian Football Club. *International Journal of Sports Physiology and Performance*.
- Robbins, J. R., Evanko, S. P., & Vogel, K. G. (1997). Mechanical loading and TGF- β regulate proteoglycan synthesis in tendon. *Archives of Biochemistry and Biophysics*, 342(2), 203-211.
- Roberts, T. J. (2002). The integrated function of muscles and tendons during locomotion. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, 133(4), 1087-1099.
- Robertson, S., Bartlett, J. D., & Gustin, P. B. (2017). Red, Amber, or Green? Athlete Monitoring in Team Sport: The Need for Decision-Support

- Systems. *International Journal of Sports Physiology and Performance*, 12(Suppl 2), S273-S279. doi: 10.1123/ijsp.2016-0541
- Roe, G. A., Phibbs, P. J., Till, K., Jones, B. L., Read, D. B., Weakley, J. J., & Darrall-Jones, J. D. (2016). Changes in adductor strength after competition in Academy Rugby Union Players. *The Journal of Strength & Conditioning Research*, 30(2), 344-350.
- Rogalski, B., Dawson, B., Heasman, J., & Gabbett, T. J. (2013). Training and game loads and injury risk in elite Australian footballers. *Journal of Science and Medicine in Sport*, 16(6), 499-503. doi: 10.1016/j.jsams.2012.12.004
- Rosager, S., Aagaard, P., Dyhre-Poulsen, P., Neergaard, K., Kjaer, M., & Magnusson, S. (2002). Load-displacement properties of the human triceps surae aponeurosis and tendon in runners and non-runners. *Scandinavian Journal of Medicine and Science in Sports*, 12(2), 90-98.
- Rosengarten, S. D., Cook, J., Bryant, A. L., Cordy, J. T., Daffy, J., & Docking, S. I. (2015). Australian football players' Achilles tendons respond to game loads within 2 days: an ultrasound tissue characterisation (UTC) study. *British Journal of Sports Medicine*, 49(3), 183-187. doi: 10.1136/bjsports-2013-092713
- Rowell, A. E., Aughey, R. J., Hopkins, W. G., Stewart, A. M., & Cormack, S. J. (2017). Identification of Sensitive Measures of Recovery After External Load From Football Match Play. *International Journal of Sports Physiology and Performance*, 12(7), 969-976.
- Ruddy, J. D., Pollard, C. W., Timmins, R. G., Williams, M. D., Shield, A. J., & Opar, D. A. (2016). Running exposure is associated with the risk of

- hamstring strain injury in elite Australian footballers. *British Journal of Sports Medicine*. doi: 10.1136/bjsports-2016-096777
- Samiric, T., Ilic, M. Z., & Handley, C. J. (2004). Characterisation of proteoglycans and their catabolic products in tendon and explant cultures of tendon. *Matrix Biology*, 23(2), 127-140.
- Sampson, J. A., Fullagar, H., & Murray, A. (2017). Evidence is needed to determine if there is a better way to determine the acute: chronic workload. *British Journal of Sports Medicine*, 51(7), 621-622.
- Saw, A. E., Main, L. C., & Gatin, P. B. (2015). Monitoring the athlete training response: subjective self-reported measures trump commonly used objective measures: a systematic review. *British Journal of Sports Medicine*, bjsports-2015-094758.
- Scott, A., Cook, J., Hart, D. A., Walker, D. C., Duronio, V., & Khan, K. M. (2007). Tenocyte responses to mechanical loading in vivo: a role for local insulin-like growth factor 1 signaling in early tendinosis in rats. *Arthritis and Rheumatism*, 56(3), 871-881.
- Scott, B. R., Lockie, R. G., Knight, T. J., Clark, A. C., & Janse de Jonge, X. A. K. (2013). A comparison of methods to quantify the in-season training load of professional soccer players. *International Journal of Sports Physiology and Performance*, 8(2), 195.
- Scott, M. T., Scott, T. J., & Kelly, V. G. (2016). The validity and reliability of global positioning systems in team sport: a brief review. *The Journal of Strength & Conditioning Research*, 30(5), 1470-1490.

- Scott, T. J., Black, C. R., Quinn, J., & Coutts, A. J. (2013). Validity and reliability of the session-RPE method for quantifying training in Australian football: a comparison of the CR10 and CR100 scales. *Journal Of Strength And Conditioning Research / National Strength & Conditioning Association*, 27(1), 270. doi: 10.1519/JSC.0b013e3182541d2e
- Selye, H. (1956). *The stress of life*.
- September, A. V., Cook, J., Handley, C. J., van der Merwe, L., Schwellnus, M. P., & Collins, M. (2009). Variants within the COL5A1 gene are associated with Achilles tendinopathy in two populations. *British Journal of Sports Medicine*, 43(5), 357-365.
- September, A. V., Mokone, G. G., Schwellnus, M. P., & Collins, M. (2006). Genetic risk factors for Achilles tendon injuries. *International SportMed Journal*, 7(3).
- Seynnes, O. R., Erskine, R. M., Maganaris, C. N., Longo, S., Simoneau, E. M., Grosset, J.-F., & Narici, M. V. (2009). Training-induced changes in structural and mechanical properties of the patellar tendon are related to muscle hypertrophy but not to strength gains. *Journal of Applied Physiology*, 107(2), 523-530.
- Smith, D. J. (2003). A framework for understanding the training process leading to elite performance. *Sports Medicine*, 33(15), 1103-1126.
- Smith, T. B., & Hopkins, W. G. (2011). Variability and predictability of finals times of elite rowers. *Medicine and Science in Sports and Exercise*, 43(11), 2155-2160.

- Stares, J., Dawson, B., Peeling, P., Heasman, J., Rogalski, B., Drew, M., . . . Lester, L. (2018). Identifying high risk loading conditions for in-season injury in elite Australian football players. *Journal of Science and Medicine in Sport, 21*(1), 46-51. doi: 10.1016/j.jsams.2017.05.012
- Steinacker, J. M., Lormes, W., Reissnecker, S., & Liu, Y. (2004). New aspects of the hormone and cytokine response to training. *European Journal of Applied Physiology, 91*(4), 382-391.
- Sun, Y., Wei, S., Zhong, Y., Fu, W., Li, L., & Liu, Y. (2015). How joint torques affect hamstring injury risk in sprinting swing–stance transition. *Medicine and Science in Sports and Exercise, 47*(2), 373.
- Taylor, C., Pizzari, T., & Cook, J. (2015). Development of a valid and reliable musculoskeletal screening protocol for Australian football. *Journal of Science and Medicine in Sport, 19*, e34.
- Taylor, K., Chapman, D., Cronin, J., Newton, M., & Gill, N. (2012). Fatigue monitoring in high performance sport: a survey of current trends. *J Aust Strength Cond, 20*(1), 12-23.
- Thornton, H. R., Delaney, J. A., Duthie, G. M., & Dascombe, B. J. (2017). Importance of Various Training-Load Measures in Injury Incidence of Professional Rugby League Athletes. *International Journal of Sports Physiology and Performance, 12*(6), 819-824. doi: 10.1123/ijsp.2016-0326
- Thornton, H. R., Delaney, J. A., Duthie, G. M., Scott, B. R., Chivers, W. J., Sanctuary, C. E., & Dascombe, B. J. (2016). Predicting self-reported

- illness for professional team-sport athletes. *International Journal of Sports Physiology and Performance*, 11(4), 543-550.
- Thorpe, R. T., Atkinson, G., Drust, B., & Gregson, W. (2017). Monitoring fatigue status in elite team sport athletes: Implications for practice. *International Journal of Sports Physiology and Performance*, 12(Suppl 2), 122-126. doi: 10.1123/ijsp.2016-0434
- Thorpe, R. T., Strudwick, A. J., Buchheit, M., Atkinson, G., Drust, B., & Gregson, W. (2016). Tracking morning fatigue status across in-season training weeks in elite soccer players. *International Journal of Sports Physiology and Performance*, 11(7), 947-952.
- Toohey, L. A., Drew, M. K., Cook, J., Finch, C. F., & Gaida, J. E. (2017). Is subsequent lower limb injury associated with previous injury? A systematic review and meta-analysis. *British Journal of Sports Medicine*, 51(23), 1670-1678. doi: 10.1136/bjsports-2017-097500
- Urhausen, A., & Kindermann, W. (2002). Diagnosis of overtraining. *Sports Medicine*, 32(2), 95-102.
- Van Mechelen, W., Hlobil, H., & Kemper, H. C. (1992). Incidence, severity, aetiology and prevention of sports injuries. *Sports Medicine*, 14(2), 82-99.
- van Schie, H. T., & Bakker, E. M. (2000). Structure-related echoes in ultrasonographic images of equine superficial digital flexor tendons. *American Journal of Veterinary Research*, 61(2), 202-209.
- van Schie, H. T., Bakker, E. M., Jonker, A. M., & van Weeren, P. R. (2001). Efficacy of computerized discrimination between structure-related and non-structure-related echoes in ultrasonographic images for the

- quantitative evaluation of the structural integrity of superficial digital flexor tendons in horses. *American Journal of Veterinary Research*, 62(7), 1159-1166.
- van Schie, H. T., Bakker, E. M., Jonker, A. M., & Weeren, P. R. v. (2003). Computerized ultrasonographic tissue characterization of equine superficial digital flexor tendons by means of stability quantification of echo patterns in contiguous transverse ultrasonographic images. *American Journal of Veterinary Research*, 64(3), 366-375.
- van Schie, H. T., Bakker, E. M., Jonker, A. M., & Weeren, P. v. (2000). Ultrasonographic tissue characterization of equine superficial digital flexor tendons by means of gray level statistics. *American Journal of Veterinary Research*, 61(2), 210-219.
- van Schie, H. T., de Vos, R.-J., de Jonge, S., Bakker, E. M., Heijboer, M., Verhaar, J., . . . Weinans, H. (2010). Ultrasonographic tissue characterisation of human Achilles tendons: quantification of tendon structure through a novel non-invasive approach. *British Journal of Sports Medicine*, 44(16), 1153-1159.
- Vanrenterghem, J., Nedergaard, N. J., Robinson, M. A., & Drust, B. (2017). Training Load Monitoring in Team Sports: A Novel Framework Separating Physiological and Biomechanical Load-Adaptation Pathways. *Sports Medicine*, 47(11), 2135–2142. doi: 10.1007/s40279-017-0714-2
- Varley, M. C., Fairweather, I. H., & Aughey¹, Robert J. (2012). Validity and reliability of GPS for measuring instantaneous velocity during acceleration,

- deceleration, and constant motion. *Journal of Sports Sciences*, 30(2), 121-127.
- Varley, M. C., Gabbett, T. J., & Aughey, R. J. (2014). Activity profiles of professional soccer, rugby league and Australian football match play. *Journal of Sports Sciences*, 32(20), 1858-1866.
- Verhagen, E., & Van Mechelen, W. (2010). *Sports injury research* (Vol. 16): Oxford University Press.
- Verrall, G. M., Kalairajah, Y., Slavotinek, J., & Spriggins, A. (2006). Assessment of player performance following return to sport after hamstring muscle strain injury. *Journal of Science and Medicine in Sport*, 9(1), 87-90.
- Verrall, G. M., Slavotinek, J., Barnes, P., Fon, G., & Spriggins, A. (2001). Clinical risk factors for hamstring muscle strain injury: a prospective study with correlation of injury by magnetic resonance imaging. *British Journal of Sports Medicine*, 35(6), 435-439.
- Veugelers, K. R., Young, W. B., Fahrner, B., & Harvey, J. T. (2016). Different methods of training load quantification and their relationship to injury and illness in elite Australian football. *Journal of Science and Medicine in Sport*, 19(1), 24-28.
- Waldén, M., Hägglund, M., & Ekstrand, J. (2005). UEFA Champions League study: a prospective study of injuries in professional football during the 2001–2002 season. *British Journal of Sports Medicine*, 39(8), 542-546.
- Waldén, M., Hägglund, M., & Ekstrand, J. (2006). High risk of new knee injury in elite footballers with previous anterior cruciate ligament injury. *British*

Journal of Sports Medicine, 40(2), 158-162. doi:
10.1136/bjism.2005.021055

Wallden, M., & Walters, N. (2005). Does lumbo-pelvic dysfunction predispose to hamstring strain in professional soccer players? *Journal of Bodywork and Movement Therapies*, 9(2), 99-108.

Whiteley, R. (2016). 'Moneyball' and time to be honest about preseason screening: it is a sham making no inroads on the 1 billion dollar injury costs in baseball. *British Journal of Sports Medicine*, 50(14), 835-836. doi:
10.1136/bjsports-2014-094541

Wiesinger, H.-P., Kösters, A., Müller, E., & Seynnes, O. R. (2015). Effects of increased loading on in vivo tendon properties: a systematic review. *Medicine and Science in Sports and Exercise*, 47(9), 1885-1895.

Williams, S., Trewartha, G., Cross, M. J., Kemp, S. P., & Stokes, K. A. (2017). Monitoring What Matters: A Systematic Process for Selecting Training-Load Measures. *International Journal of Sports Physiology and Performance*, 12(Suppl 2), S2-101-S102-106.

Williams, S., West, S., Cross, M. J., & Stokes, K. A. (2017). Better way to determine the acute: chronic workload ratio? *British Journal of Sports Medicine*, 51(3), 209-210.

Wilson, G., Wood, G., & Elliott, B. (1991). The relationship between stiffness of the musculature and static flexibility: an alternative explanation for the occurrence of muscular injury. *International Journal of Sports Medicine*, 12(04), 403-407.

- Windt, J., & Gabbett, T. J. (2017). How do training and competition workloads relate to injury? The workload—injury aetiology model. *British Journal of Sports Medicine*, 51(5), 428-435. doi: 10.1136/bjsports-2016-096040
- Windt, J., & Gabbett, T. J. (2018). Is it all for naught? What does mathematical coupling mean for acute:chronic workload ratios? *British Journal of Sports Medicine*. doi: 10.1136/bjsports-2017-098925
- Windt, J., Gabbett, T. J., Ferris, D., & Khan, K. M. (2017). Training load--injury paradox: is greater preseason participation associated with lower in-season injury risk in elite rugby league players? *British Journal of Sports Medicine*, 51(8), 645-650. doi: 10.1136/bjsports-2016-095973
- Windt, J., Zumbo, B. D., Sporer, B., MacDonald, K., & Gabbett, T. J. (2017). Why do workload spikes cause injuries, and which athletes are at higher risk? Mediators and moderators in workload-injury investigations. *British Journal of Sports Medicine*, 51(13), 993-994. doi: 10.1136/bjsports-2016-097255
- Witvrouw, E., Danneels, L., Asselman, P., D'Have, T., & Cambier, D. (2003). Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players. *The American Journal Of Sports Medicine*, 31(1), 41-46.
- Witvrouw, E., Mahieu, N., Roosen, P., & McNair, P. (2007). The role of stretching in tendon injuries. *British Journal of Sports Medicine*, 41(4), 224-226. doi: 10.1136/bjism.2006.034165
- Wollin, M., Thorborg, K., & Pizzari, T. (2017). The acute effect of match play on hamstring strength and lower limb flexibility in elite youth football players.

- Scandinavian Journal of Medicine and Science in Sports*, 27(3), 282-288.
doi: 10.1111/sms.12655
- Woo, S.-Y. (1986). Biomechanics of tendons and ligaments *Frontiers in biomechanics* (pp. 180-195): Springer.
- Woods, C., Hawkins, R., Hulse, M., & Hodson, A. (2002). The Football Association Medical Research Programme: an audit of injuries in professional football—analysis of preseason injuries. *British Journal of Sports Medicine*, 36(6), 436-441.
- Worrell, T. W., Smith, T. L., & Winegardner, J. (1994). Effect of hamstring stretching on hamstring muscle performance. *Journal of Orthopaedic and Sports Physical Therapy*, 20(3), 154-159.
- Ying, M., Yeung, E., Li, B., Li, W., Lui, M., & Tsoi, C.-W. (2003). Sonographic evaluation of the size of Achilles tendon: the effect of exercise and dominance of the ankle. *Ultrasound in Medicine and Biology*, 29(5), 637-642.
- Young, W. B., Newton, R. U., Doyle, T., Chapman, D., Cormack, S., Stewart, C., & Dawson, B. (2005). Physiological and anthropometric characteristics of starters and non-starters and playing positions in elite Australian Rules football: a case study. *Journal of Science and Medicine in Sport*, 8(3), 333-345.
- Zhang, Z., Ng, G., & Fu, S. (2015). Effects of habitual loading on patellar tendon mechanical and morphological properties in basketball and volleyball players. *European Journal of Applied Physiology*, 115(11), 2263-2269.