Strength and Structure: Unravelling Lumbar Musculature and Lower Limb Injury Risk in Elite Team Sports

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Published

2023-08-23

Thesis Type

Thesis (PhD Doctorate)

School

School of Health Sci & Soc Wrk

DOI

10.25904/1912/5012

Strength and Structure: Unravelling Lumbar Musculature and Lower Limb Injury Risk in Elite Team Sports

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Submitted in fulfilment of the requirements of the degree of Doctor of Philosophy

28th of May 2023

Abstract

Background: Australian Football League (AFL) and National Rugby League (NRL) are elite Australian competitions for rugby league and Australian rules football. Non-contact injuries, like muscle strains and ligament sprains, are very common but the cause of these injuries difficult to identify. There is preliminary evidence in AFL athletes, that reduced cross-sectional area of the lumbar multifidus at the fifth vertebrae and increased cross-sectional area of the quadratus lumborum measured via ultrasound imaging, is a risk factor for sustaining any non-contact lower limb injuries. The lumbar multifidus and quadratus lumborum are both involved in trunk extension, rotation, and proprioception and believed to influence hip and trunk kinematics during exercise. However, there is limited evidence showing a mechanistic link between lumbar muscle cross-sectional area and pooled non-contact lower limb injuries. Assessing the force generating capacity of lumbar spine muscles may provide a better understanding to why the lumbar multifidus at the fifth lumbar vertebral level and quadratus lumborum are potential risk factors for lower limb injuries. Previous studies have only assessed lumbar muscle morphology in single sport cohorts (Australian rules football) that mainly consisted of small sample sizes. With most the literature reporting the same sport, there are uncertainties about the applicability in other sports.

This thesis aims to (1) develop a novel trunk and hip extensor strength test and assess its reliability, (2) replicate a previously established model to assess non-contact lower limb injury risk in elite team sports based on lumbar muscle morphology, (3) develop a predictive model for hamstring strain and knee ligament injury risk based on lumbar muscle morphology and strength, and (4) systematically review and meta analyse the literature on lumbar muscle characteristics as a risk factor for non-contact lower limb injuries.

Abstract

Methods: (1) Reliability of a novel trunk and hip extensor strength test

Ultrasound imaging of 10 healthy recreationally active adults were obtained and 20 healthy recreationally active adults participated in the isometric trunk and hip extensor strength testing. Participants had no history of lower limb injury in the prior 12 months. All participants were provided with plain language information prior to obtaining informed written consent. ultrasound imaging was obtained on two separate sessions between 24 and 48 hours apart with two sonographers assessing inter-rater reliability during the first session. The isometric trunk and hip extensor strength testing was conducted on two separate sessions between five and seven days apart.

(2) Replication of the assessment of non-contact lower limb injury risk in elite team sports based on lumbar muscle morphology

AFL (n=87) and NRL (n=151) players underwent preseason ultrasound measures of the cross sectional area of the lumbar multifidus muscle (from second to fifth lumbar vertebral level) and quadratus lumborum muscle. Each club's medical staff reported all non-contact lower limb injuries sustained in the subsequent regular season (excluding finals). lumbar multifidus and quadratus lumborum cross-sectional area, age, body mass index and non-contact lower limb injuries were analysed using multivariable logistic regression.

(3) Develop a predictive model for hamstring strain and knee ligament injury risk based on lumbar muscle morphology and strength

During the AFL and NRL 2020 preseasons, players underwent assessments of isometric trunk and hip extension strength, and trunk morphology (n=126). Isometric trunk and hip extension strength assessments included a 55s Maximum Voluntary Isometric Contraction (MVIC) protocol (5s MVIC, 5s rest, 45s MVIC). Trunk morphology included lumbar multifidus at fifth lumbar vertebral level and quadratus lumborum cross-sectional area obtained via two-dimensional ultrasound. Associations between 5s peak MVIC (maximum strength), 45s mean MVIC (strength-endurance), lumbar multifidus at fifth lumbar vertebral level and quadratus lumborum cross-sectional area, age, previous injury, and subsequent hamstring strain and knee ligament injury were assessed using logistic regression and decision tree models.

(4) Lumbar muscle characteristics as a risk factor for non-contact lower limb injuries: systematic review and meta-analysis

The systematic review was performed in accordance with PRISMA guidelines and pre-registered with PROSPERO (ID: CRD42020197393). Online databases PubMed (MEDLINE), Scopus, EBSCOhost (SPORTDiscus), and EMBASE were systematically searched from inception to February 2022 according to the PICO framework for prognostic studies to develop a comprehensive search strategy consisting of the following parameters; population: adult team sports athletes, problem: lower limb non-contact musculoskeletal injuries, prognostic factor: size measures of the lumbar spine muscles, comparison: comparison of injured and uninjured groups, outcome: lumbar spine muscle size mean differences. Screening of articles was performed using the Covidence (Cochrane, London, England) web-based application including the application's own deduplication tool. Two reviewers performed all screening steps of the relevant articles. The Quality of Prognosis Studies (QUIPS) tool was used to identify bias in the included studies and a meta-analysis and best evidence synthesis were performed to summarise the results.

Results: (1) Reliability of a novel trunk and hip extensor strength test

Intra-rater reliability for lumbar multifidus L5 (intraclass correlation coefficient (ICC)=0.96, coefficient of variation (CV)=1.05%, minimally detectable change (MDC)=0.17cm^2, MDC%=2.3%) and quadratus lumborum cross-sectional area (ICC=0.95, CV=0.8%, MDC=0.09cm^2, MDC%=1.4%) showed excellent reliability. Inter-rater reliability (lumbar multifidus L5: ICC=0.86, CV=2.24%, MDC=0.35cm^2, MDC%=4.6%; quadratus lumborum: ICC=0.96, CV=1.5%, MDC=0.20cm^2, MDC%=3.2%) were also excellent. Further, reliability for maximum strength (ICC=0.93, CV=6.8%, MDC=0.87N/kg, MDC%=12.1%) and strength endurance (ICC=0.90, CV=8.6%, MDC=0.63N/kg, MDC%=17.2%) from the modified Sorensen test demonstrated excellent results.

(2) Replication of the assessment of non-contact lower limb injury risk in elite team sports based on lumbar muscle morphology

Seventy-two players sustained a non-contact lower limb injury in the 2020 regular season (AFL=21, NRL=51). The multivariable logistic regression (odds ratio (OR)=1.36, 95% confidence interval (95%CI)=1.02-1.85, p=0.038) identified AFL players with larger quadratus lumborum cross-sectional area at increased risk of sustaining a non-contact lower limb injury during the regular season but no relationship was found for lumbar multifidus cross-sectional area and non-contact lower limb injuries in the AFL (OR=1.01, 95%CI=0.36-2.78, p=0.591) or NRL (OR=0.63, 95%CI=0.29-1.33, p=0.149).

(3) Develop a predictive model for hamstring strain and knee ligament injury risk based on lumbar muscle morphology and strength

Nineteen hamstring and 13 knee ligament injuries occurred. Greater strength endurance (OR=0.42, 95%CI=0.23-0.74, p=0.004) and maximum strength (OR=0.55, 95%CI=0.31-0.94, p=0.039) reduced hamstring injury risk. Knee ligament injury risk increased with larger lumbar multifidus L5 (OR=1.66, 95%CI=1.14-2.45, p=0.008) and lumbar multifidus at fifth lumbar vertebral level to quadratus lumborum ratio (OR=1.57, 95%CI=1.13-2.23, p=0.008). Decision tree models suggested low strength endurance (<99Nm) were characteristic of hamstring strains yet those with high (≥1.33) lumbar multifidus at fifth lumbar vertebral level to quadratus lumborum ratio were protected. Knee ligament injuries were classified by larger (≥8.49cm^2) lumbar multifidus L5 cross-sectional area, greater (≥1.25) lumbar multifidus at fifth lumbar vertebral level to quadratus lumborum ratio, and lower maximum strength (<9.24 N/kg).

(4) Lumbar muscle characteristics as a risk factor for non-contact lower limb injuries: systematic review and meta-analysis

Eight studies with a total of 842 players and 401 lower limb injuries were observed, with five proposed risk factors meeting the inclusion criteria. Overall estimates for smaller lumbar multifidus at fifth lumbar vertebral level cross-sectional area (OR=1.15, 95%CI=1.13-1.16, p=0.039) and larger quadratus lumborum cross-sectional area (OR=1.09, 95%CI=1.07-1.10, p=0.038) showed statistically significant associations with lower limb injury risk. In total, five factors were included in the best evidence synthesis, three of which could not be included in the meta-analysis. Only quadratus lumborum cross-sectional area showed a consistently strong association with lower limb injury risk, and lumbar multifidus L5 asymmetry showed a strong lack of association with lower limb injury risk.

Discussion and conclusion: This thesis is the first to develop a field test measuring isometric trunk and hip extensor strength and assess associations between isometric trunk and hip extensor strength and non-contact lower limb injuries. A reliable test was developed and showed reduced strength endurance in this muscle group can be considered a risk factor for sustaining a subsequent hamstring strain injury in a pooled AFL and NRL cohort. In addition, this thesis attempted to replicate previous findings of lower lumbar multifidus L5 and increased quadratus lumborum cross-sectional area as risk factors for non-contact lower limb injuries in AFL and NRL players. Significant association between increased quadratus lumborum cross-sectional area and prospective non-contact lower limb injuries in AFL players was observed but no significant association was found in NRL players. Larger lumbar multifidus L5 cross-sectional area or bigger lumbar multifidus at fifth lumbar vertebral level to quadratus lumborum ratio only showed an association with pooled non-contact knee ligament injury risk and did not show an association with general non-contact lower limb injury risk. Despite the failed replication in of smaller lumbar multifidus L5 cross-sectional area as a risk factor for pooled non-contact lower limb injury risk the meta-analysis found an overall significant effect for smaller lumbar multifidus L5 cross-sectional area as a risk factor for pooled non-contact lower limb injures. Future research is required to further explore the relationship between the current measures and validate the models in other running-based team sports such as soccer or Gaelic football to better understand if trunk and hip extensor strength endurance is a football code specific or generalised risk factor.

Statement of Originality

This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

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Martin Hajek

28th May 2023

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Acknowledgements

My first and foremost thanks for completing this thesis go out to my supervisory team: Steven Duhig, Llion Roberts, Matthew Bourne and Norman Morris. I want to especially thank Steven Duhig for coming up with the idea for this project and initially approaching me; without your support I would not have been able to move to Australia and start this candidature.

Thanks to my external contributors who helped to conduct this research. Morgan Williams for his supervision in the statistical analysis and Cassandra Mingin for her help in collecting ultrasound imaging data on the road.

I want to thank all the AFL and NRL players who volunteered to participate in our data collection as well as the club staff who helped compile the injury reports; without them volunteering their time and effort, none of this research would have been possible. It was a special experience to work with so many elite athletes and visit the club facilities. Special thanks to all my colleagues who volunteered their time to participate in the reliability study and those who let me practice my ultrasound skills on them.

My biggest gratitude goes out to my family back home in Vienna, Austria. My parents Maria and Josef who fully supported my move to a different continent, my grandmother Christine (I hope I sent enough postcards), and my uncles, aunts, and cousins. Travel restrictions caused more time apart than anticipated and I know it was very difficult at times.

Personally, I need to thank my partner Gina Ricardo and her dog Mei Mei for their emotional support even during the toughest times of the candidature. My experience would not have been the same without you.

Acknowledgements

Big thanks to my friends back home in Vienna who keep me updated about the life back home and still manage to stay in contact with me even though the time zone difference is not favourable. Especially thanking Lisa who helped proofreading parts of this document and my other close friends Amadea, Patrick, and Kathi.

Lastly, I want to acknowledge the amazing community at Alpine Indoor Climbing who made me feel at home immediately after moving over. Jamie and Kirsty, thank you for building this community and supporting rock climbing at the Gold Coast.

Publications

All Papers Included are Co-Authored.

Acknowledgement of Papers included in this Thesis.

Section 9.1 of the Griffith University Code for the Responsible Conduct of Research (“Criteria for Authorship”), in accordance with Section 5 of the Australian Code for the Responsible Conduct of Research, states:

To be named as an author, a researcher must have made a substantial scholarly contribution to the creative or scholarly work that constitutes the research output and be able to take public responsibility for at least that part of the work they contributed. Attribution of authorship depends to some extent on the discipline and publisher policies, but in all cases, authorship must be based on substantial contributions in a combination of one or more of:

- conception and design of the research project
- analysis and interpretation of research data
- drafting or making significant parts of the creative or scholarly work or critically revising it so as to contribute significantly to the final output.

Section 9.3 of the Griffith University Code (“Responsibilities of Researchers”), in accordance with Section 5 of the Australian Code, states:

Researchers are expected to:

- Offer authorship to all people, including research trainees, who meet the criteria for authorship listed above, but only those people.
- accept or decline offers of authorship promptly in writing.
- Include in the list of authors only those who have accepted authorship.

- Appoint one author to be the executive author to record authorship and manage correspondence about the work with the publisher and other interested parties.
- Acknowledge all those who have contributed to the research, facilities, or materials but who do not qualify as authors, such as research assistants, technical staff, and advisors on cultural or community knowledge. Obtain written consent to name individuals.

Included in this thesis are papers in Chapters Four, Five, Six and Seven which are co-authored with other researchers. My contribution to each co-authored paper is outlined at the front of the relevant chapter. The bibliographic details (if published or accepted for publication)/status (if prepared or submitted for publication) for these papers including all authors, are:

Chapter Four: Submitted

Hajek, M., Roberts L. R., Bourne, M. N., Morris, N. R., Duhig, S. J. (2023). Reliability of diagnostic two-dimensional ultrasound imaging to assess cross sectional area of the lumbar multifidus and quadratus lumborum muscles and isometric trunk and hip extensor strength testing. *Unpublished*

Chapter Five: Published

Hajek M, Williams MD, Bourne MN, Roberts LA, Morris NR, Shield AJ, Mingin CV, Headrick J, Duhig SJ. Predicting Noncontact Lower Limb Injury Using Lumbar Morphology in Professional Australian Football and Rugby League Players. Med Sci Sports Exerc. 2022 May 1;54(5):814-820. DOI: 10.1249/MSS.0000000000002847. Epub 2021 Dec 23. PMID: 34935708.

Chapter Six: Submitted

Hajek, M., Williams, M. D., Bourne, M. N., Roberts L. R., Morris, N. R., Shield, A. J., Headrick, J., Duhig, S. J. (2023). Associations between hamstring strain and knee ligament injuries with isometric trunk and hip strength and morphology in professional Australian rules football and rugby league players. *Unpublished*

Chapter Seven: Submitted

Hajek, M., Collings, T. J., Roberts L. R., Bourne, M. N., Morris, N. R., Duhig, S. J. (2023). Associations between hamstring strain and knee ligament injuries with isometric trunk and hip strength and morphology in professional Australian rules football and rugby league players. *Unpublished*

Appropriate acknowledgements of those who contributed to the research but did not qualify as authors are included in each paper.

(Signed) [redacted] Date: 28/05/2023

Martin Hajek, PhD candidate

(Countersigned) [redacted] Date: 28/05/2023

Llion Roberts, Co-principal supervisor

List of Abbreviations and Acronyms

ACL	Anterior Cruciate Ligament
AFL	Australian Football League
AUC	Area Under the Curve
BMI	Body Mass Index
CI	Confidence Interval
CSA	Cross-Sectional Area
CV	Coefficient of Variation
EMG	Electromyography
GPS	Global Positioning System
ICC	Intraclass Correlation Coefficient
L5	Fifth Lumbar Vertebrae
LCL	Lateral Collateral Ligament
LM	Lumbar Multifidus
MCL	Medial Collateral Ligament
MDC	Minimally Detectable Change
MVIC	Maximum Voluntary Isometric Contraction
NRL	National Rugby League
OR	Odds Ratio
PCL	Posterior cruciate Ligament
QL	Quadratus Lumborum
ROC	Receiver Operator Characteristics
USI	Ultrasound Imaging

Chapter One

General Introduction

1.1. Background

In Australia, the term football is collectively used for several popular team sports including Australian rules football, rugby league, rugby union, and soccer. Australian rules football and rugby league are the most popular team sports and their respective elite competitions – the Australian Football League (AFL), and National Rugby League (NRL) – generate high spectator interest and revenue (Densten, 2021; Read et al., 2021). Match-play in the AFL consists of two teams of 18 players per side competing against each other on an oval-shaped field. NRL teams have 13 players competing per side with the match being played on a rectangular field. Both professional leagues are played through March to September (Australian autumn to spring) with the AFL having 18 teams while the NRL consists of 16 teams.

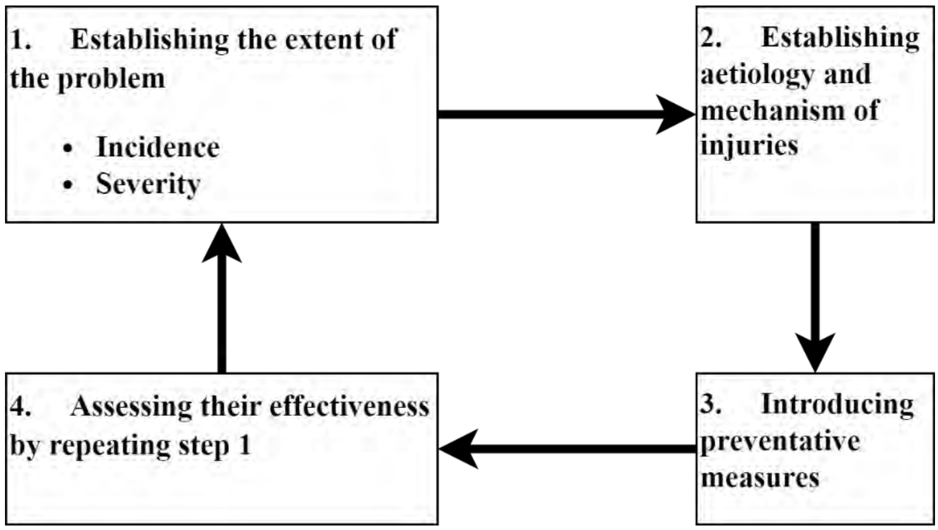
The main activity during Australian rules football and rugby league is running but running loads substantially differ between sports based on the different fields and match demands. Australian rules football is played on an oval field of large dimensions (135 to 185 m long and 110 to 155 m wide) whereas rugby league is played on a rectangular field that is significantly smaller (100m long and 68m wide). While both sports have a playing time of 80-minutes, Australian rules football has a longer duration due to time-on (time added to account for stoppages, injuries or goals to be scored), which is one factor leading to increased running loads. Based on Global Positioning System (GPS) data, elite Australian rules football players cover a total distance of 11 to 12km in 99 to 104min of running time per match, depending on playing position, and up to 90 high speed surges (Wisbey et al., 2010). In elite rugby league, about 4 to 7km are covered in 38 to 73min of running time with high-speed bouts every 5 to 9min (Gabbett et al., 2012). Rapid change of direction requires agility and acceleration leading to these high intensity bouts common in both sports (Gabbett, 2005). Jumping and explosive power is required in both competitions to contest for ball possession in various match situations (Hiscock et al., 2017).

Lower limb injuries are the most common cause of time loss from training and competition in AFL and NRL (King et al., 2022; McCaskie et al., 2021). More than two thirds of injuries in Australian rules football (McCaskie et al., 2021) involve the lower limb with the most common being hamstring or quadricep muscle strains and the most commonly affected joint being the knee (King et al., 2022; Saw et al., 2018). Over 50% of lower limb injuries have a non-contact mechanism and caused by either high-speed running, jumping or side-cutting (Orchard & Seward, 2009; Saw et al., 2018).

Any injury sustained by a player has an impact on the team's performance as well as an economic impact on the club. Player injuries account for an estimated 12% of the variation in the team's final ladder position and are a significant determinant of whether a team reaches the finals (Hoffman et al., 2020). Hamstring strain injuries are the most common injuries in the AFL (7.35 per club per season) and are responsible for the second largest time loss (28.03 missed matches per club per season) (McCaskie et al., 2021). Knee ligament injuries cause the most time loss in the AFL (35.38 missed matches per club per season) which despite the lower incidence rate (4.75 per club per season) is due to their high severity (15.11 missed matches per club per season for an anterior cruciate ligament (ACL) injury) (McCaskie et al., 2021). Financially, a hamstring strain injury is estimated to incur a $40,000 burden for an AFL club based on the number of matches missed by players with a hamstring strain injury (Hickey et al., 2014). With Australia having the highest incidence of ACL injuries in the western world (Janssen et al., 2012) and the cost of ACL reconstruction estimated at $38,000 (Mather et al., 2013), reducing these rates is of high importance to professional clubs and society.

A general framework (Figure 1) on the scientific basis of reducing injury risk in elite athletes was developed by van Mechelen et al. (1992). This approach consisted of four steps: 1) establishing the extent of the problem (injury incidence and severity), 2) establishing the cause and mechanism(s) of injury, 3) introducing a preventative measure, and 4) assessing its effectiveness. Many studies conducted in this area focus on the first step of the process by detailing injury epidemiology or the second step, aiming to establish risk factors, but very few aim to externally validate the risk factor, or test the efficacy of injury prevention programmes in a randomised controlled trial (Losciale et al., 2023). When studies aim to identify an injury risk factor, they are often working with limited sample sizes (Bahr & Holme, 2003) and examine population level association between injury risk and a factor measured in a screening test (Bahr, 2016). There is often a lack of causality between the identified risk factor and the specific injury (Stovitz et al., 2019) and many studies oversimplify the association with an injury by only considering factors in isolation where injury likely occurs due to complex, non-linear interactions between factors (Ruddy et al., 2019). Currently, there is a lack of evidence validating previously established risk factors and many of those identified have an unknown causality to the injury in question (Losciale et al., 2023). To lastingly change impact injury rates in the field, injury mitigation strategies should be developed in conjunction with the target group and uptake in the real-world (Finch, 2011).

Figure 1: Injury prevention framework for sports and exercise science



Note: Adapted from van Mechelen et al. (1992)

Risk factors for lower limb injuries are multifactorial and can be categorised into non-modifiable and modifiable. Non-modifiable risk factors such as age or previous lower limb injury have consistently been the most accurate predictors for sustaining a subsequent injury (Green et al., 2020; Green & Pizzari, 2017; Smith et al., 2012a; Whittaker et al., 2015) although prescribed interventions are unable to change these. Therefore, injury prevention strategies need to focus on modifiable risk factors for lower limb injuries that can be monitored over time. Modifiable risk factors for hamstring strain injuries include weakness of the knee flexor muscles at baseline testing or increased high-speed running loads (Green et al., 2020) and ACL injuries were associated to risk factors such as: reduced neuromuscular control of the trunk, strength deficits in hip abductor muscles, pre-activity of hamstring muscles, increased knee valgus moment or abnormal landing kinematics (Pfeifer et al., 2018).

A recently suggested modifiable risk factor for lower limb injuries was smaller cross-sectional area of the lumbar multifidus muscle at the fifth lumbar vertebral level and larger cross-sectional area of the quadratus lumborum (Hides & Stanton, 2017; Hides et al., 2014). While the preliminary evidence surrounding smaller lumbar multifidus muscle at the fifth lumbar vertebral level and larger quadratus lumborum as a risk factor for lower limb injuries shows promising results it is still in phase two of the injury prevention framework. The mechanism between the risk factor and lower limb injury risk has not been established yet and no preventative programmes have been reported in the literature. Most studies have been conducted in Australian rules football (Hides et al., 2020; Hides et al., 2011; Hides & Stanton, 2017; Hides et al., 2014) with few in other sports (Low et al., 2023; Olivier et al., 2017; Roy et al., 2021), warranting replication of the suggested risk factor in different cohorts.

Roy et al. (2021) suggested that limited contractile ability of the lumbar multifidus may also be associated with lower limb injury risk. Both the lumbar multifidus and quadratus lumborum are active in trunk extension (Maughan et al., 1983; Phillips et al., 2008) and the Sorensen test (Biering-Sorensen, 1984) is a popular test that assesses trunk and hip extensor strength endurance. The Sorensen test has shown to be a reliable (Keller et al., 2001b; Latimer et al., 1999; Martinez-Romero et al., 2020) and valid (Champagne et al., 2008; Coorevits et al., 2008; Latimer et al., 1999; Pitcher et al., 2007) assessment that only requires a plinth and is thus easily performed in a field-based setting. However, there are some limitations to this test, like its inability to elicit maximal voluntary isometric contraction (MVIC) of the trunk extensor muscles (Keller et al., 2001b), failure to eliminate hip extensor involvement (Moreau et al., 2001), and a bias towards female participants performing better in the test than male participants for which the reasons are not yet understood (Demoulin et al., 2006). Modifying the Sorensen test can address some of these limitations (Champagne et al., 2008) and provide a viable option for future testing. Assessing lumbar multifidus and quadratus lumborum muscle strength in addition to measuring muscle size may improve estimations of lower limb injury risk.

1.2. Thesis Aims and Hypotheses.

This thesis aims to address several gaps in the literature surrounding lumbar muscle morphology and function as risk factors for lower limb injuries. A series of studies were conducted to (1) develop a novel trunk and hip extensor strength test and assess its reliability, (2) replicate a previously established model to assess non-contact lower limb injury risk in elite team sports based on lumbar muscle morphology, (3) develop a predictive model for hamstring strain and knee ligament injury risk based on lumbar muscle morphology and strength, and (4) systematically review and synthesise the literature on lumbar muscle characteristics as a risk factor for non-contact lower limb injuries.

Aim 1: To develop a novel trunk and hip extensor strength test and assess its reliability.

Hypothesis: The newly developed trunk and hip extensor strength test will show greater than a moderate level of reliability.

Aim 2: To replicate a previously established model to assess non-contact lower limb injury risk in elite team sports based on lumbar muscle morphology.

Hypothesis: Players with a smaller lumbar multifidus muscle at the fifth lumbar vertebral level and larger quadratus lumborum will demonstrate higher risk of subsequently sustaining a non-contact lower limb injury.

Aim 3: To develop a predictive model for hamstring strain and knee ligament injury risk based on lumbar muscle morphology and strength.

Hypothesis 1: Players with lower pre-season trunk and hip extensor maximum strength and strength endurance will have a higher risk of sustaining a subsequent hamstring strain or knee ligament injury.

Hypothesis 2: Combining measures of lumbar muscle morphology and lumbar muscle strength in a predictive model will increase sensitivity and specificity of the model.

Aim 4: To systematically review and meta analyse the literature on lumbar muscle characteristics as a risk factor for non-contact lower limb injuries.

Hypothesis: Systematic review, and therefore no hypothesis.

1.3. Empirical Approach

In order to reach the aims stated above, three separate data collections resulting in four chapters were conducted during the candidature:

Study 1) Reliability of Diagnostic Two-Dimensional Ultrasound Imaging to Assess Cross-Sectional Area of the Lumbar Multifidus and Quadratus Lumborum Muscles and Isometric Trunk and Hip Extensor Strength Testing.

Study 2) Predicting Non-Contact Lower Limb Injury Using Lumbar Morphology in Professional Australian Football and Rugby League Players.

Study 3) Associations Between Hamstring Strain and Knee Ligament Injuries with Isometric Trunk and Hip Strength and Morphology in Professional Australian Rules Football and Rugby League Players.

Study 4) Lumbar Multifidus and Quadratus Lumborum Associations with Lower Limb Injury Risk in Team Sports: A Systematic Review and Meta-Analysis.

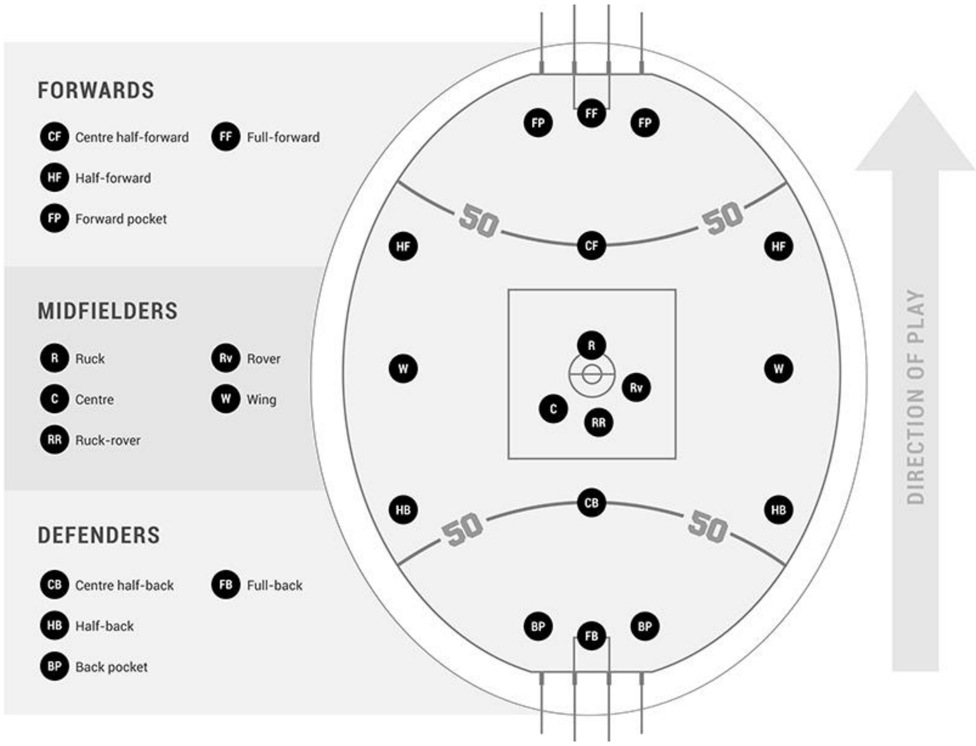
Chapter Two

Literature Review

2.1. Australian Rules Football

Australian rules football is a team sport played at all levels, with the elite competition called the AFL. The objective of the game is to score points by kicking a ball between two goalposts, with players allowed to advance the ball by either kicking or hand passing (Norton et al., 1999). Teams consist of 22 players with 18 per side on the field and four on the bench and 75 bench interchanges allowed (Norton et al., 1999). The game is played on an oval cricket field, with no standard dimensions, that is larger than conventional rectangular soccer or rugby fields. Position groups in Australian rules football can be broken down into forwards (offensive), middle (nomadic) players and backs (defensive) (Gray & Jenkins, 2010) (Figure 2). If a player catches the ball in the air from a kick of more than 15 metres, it is called a "mark" and the player gets the chance to have an uninterrupted kick as a reward (Gray & Jenkins, 2010). The game is played over four 20-minute quarters that can include extra time, making the game last between 80 and 120+ minutes of play time with time stops at instances like a scored goal or boundary throw-in (Gray & Jenkins, 2010). At the restart of play, such as when a goal is kicked or the ball goes out of bounds, two opposing nomadic players called ruckmen contest for the ball by jumping towards the ball that is thrown up by a umpire (similar to a basketball tip-off) (Gray & Jenkins, 2010). Australian rules football allows for a limited amount of contact, with players only allowed to tackle the ball carrier between shoulders and knees, blocking opponents within five metres of the ball by pushing or bumping (shepherding), and pushing off other players while jumping to contest for a mark (marking contest) (Gray & Jenkins, 2010).

Figure 2: Playing positions in Australian rules football.



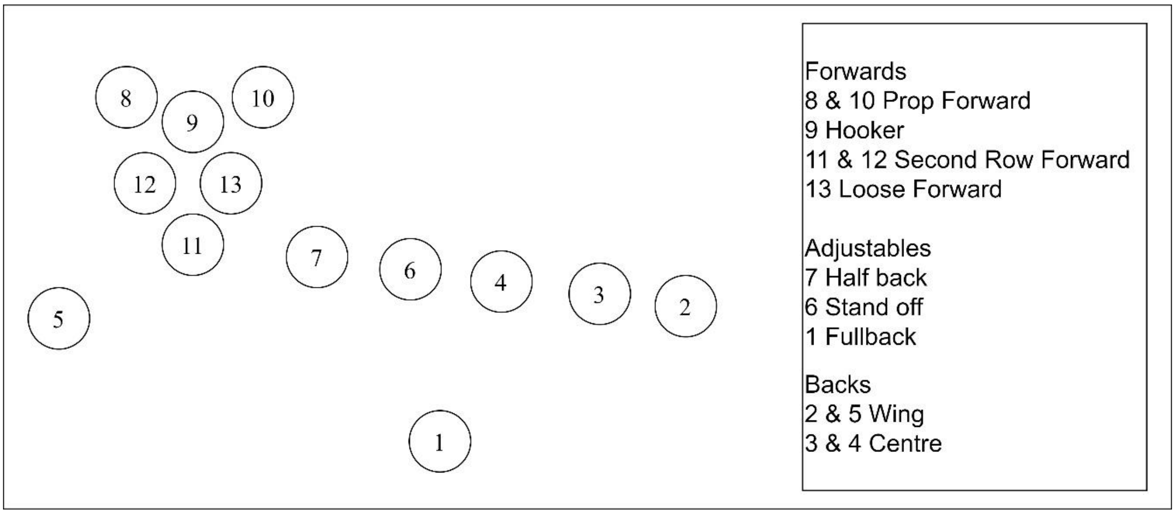
Source: https://www.hartsport.com.au/info-tips/australian-rules accessed on 23/05/2023

With a maximum of 75 bench interchanges allowed in Australian rules football, players typically spend about 100 of the 120 minutes of match time on the field (Coutts et al., 2015; Coutts et al., 2010). GPS data insights into the exact breakdown of the running components of a match (Wisbey et al., 2010) show running loads in elite Australian rules football as intermittent with a combination of short high-intensity periods and longer periods of jogging and walking (Dawson et al., 2004). A study by Wisbey et al. (2010) and colleagues reported that most time (65%) was spent at low speeds (<8 km/h) and players averaged 85 high speed efforts (>18 km/h) per game. Total running distances per match were between 11 and 12 km per match with a trend over the last decade towards more high-speed efforts per match (Janetzki et al., 2021; Wisbey et al., 2010). The increase in high-speed efforts during a match also created the necessity to shift training focus more towards high-speed running (Johnston et al., 2018). Increased running loads at high-speed highlight the importance of aerobic fitness and recovery between efforts (Pyne et al., 2005; Young et al., 2005). For instance, players that perform better in a 2x2 minute run rest managed to have 20% better kicking accuracy during the match (Young & Rogers, 2014). In the talent identification process players that showed higher agility measures, higher 10 metre speed, higher distances covered during the beep test and had more lean body mass were more likely to start games in the AFL (Burgess et al., 2012). Due to the skill dependence of the game variables measuring strength are less used to predict future performance than in other competitions but these findings underscore the compelling link between physiological fitness, specifically aerobic capabilities, and skill execution under conditions of physical exertion.

2.2. Rugby League Football

The origins or rugby league football can be traced back to the north of England at the end of the 19th century, with the elite competition in Australia called the NRL (Gabbett, 2005). A rugby league match is played in two 40-minute halves on a rectangular field with teams consisting of 13 players. The aim of the game is to score a "try" by advancing the ball to the other team's territory with only backwards passes allowed. Players are allowed to perform tackles on the ball carrier and after a series of six tackles the ball is given to the opposing team (Gibbs, 1993). A forward kick is allowed to give possession of the ball to the other team with the aim of placing them in a worse field position. Players can be grouped into either forwards or backs with individual positions available withing these groups (Figure 3). Forwards are involved in most of the head on collisions while backs are more likely to spend their game running freely. A total of eight substitutions are allowed at the elite level and the amount of collisions in rugby league is considered to be "very high" making it one of the most physical games played (Orchard & Seward, 2009).

Figure 3: Rugby league football playing positions when attacking from the scrum.



The running loads differ greatly between position groups in rugby league but are consistent within the position groups with average distances covered for forwards, adjustable players and backs being 3569 metres, 6411 metres, and 6819 metres respectively (Gabbett et al., 2012). GPS data was used to evaluate running distances, running times, and running speeds in elite rugby league showing consistent results in most studies (Gabbett et al., 2012; King et al., 2009; Sykes et al., 2009). Running speeds ranged between 93 m/min for outside backs and 101 m/min for adjustable players, with outside backs covering larger distances at lower speeds but having more high-speed bursts (Gabbett et al., 2012). Repeated high-speed running efforts are especially common in outside backs and fullbacks. Forwards in contrast to backs, experience more collisions during match play and collide with opposition players every minute compared to backs and adjustable player experiencing a collision every two minutes (Austin et al., 2011; Gabbett et al., 2011; King et al., 2009). The combination of forwards tackling and sprinting leads to repeated high intensity efforts every five to six minutes, while backs have a more consistent running speed with high intensity bouts between seven and nine minutes (Gabbett et al., 2011). A study by Gabbett and Seibold (2013) investigated the physical performance of players selected for semi-professional rugby league teams and found players selected for semi-professional matches had significantly higher three repetition maximum back squat, higher three repetition maximum chin-up, more bench press repetitions at the player's weight, higher vertical jump heights, and better performance in the Yo-Yo intermittent recovery test (Krustrup et al., 2003) compared to players who did not get selected for these matches. These findings suggesting maximum strength, explosive power and the ability to recover between high intensity efforts the key physical characteristics for those playing at higher competitive levels.

2.3. Injury Surveillance in Australian Rules Football and Rugby League Football

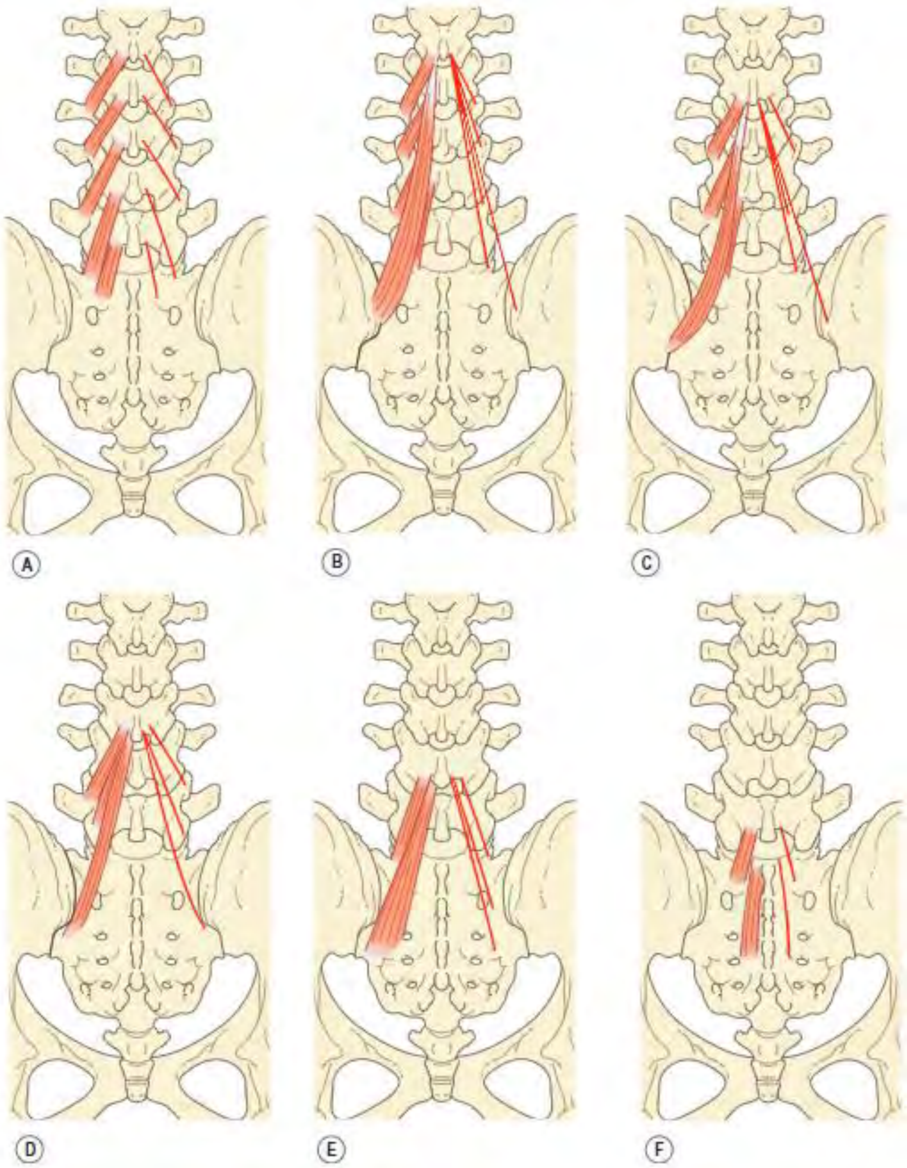
Injury surveillance in the AFL is thorough compared to other elite level competitions with the league annually releasing standardised injury reports since 1996, providing researchers with a large database (Orchard & Seward, 2009). In comparison, the NRL started publicly releasing injury reports in 2012 allowing for fewer historical comparisons (King et al., 2022). In the AFL, all players consent to the usage of their anonymised injury data to be used for research under guidance by the AFL Research Board (AFL, 2020). An injury is defined as "any physical or medical condition that cause a player to be unavailable for a match in the regular season or finals" (Saw et al., 2018). To standardise injury definitions the Orchard sports injury classifications system (OSICS) is used universally by all AFL clubs (Orchard et al., 2010). Incidences of injuries in the AFL have been fairly consistent over the last decade, ranging from 35 to 40 injuries per club per season (McCaskie et al., 2021) with the majority of injuries affecting the lower limb (27.7 per club per season). Hamstring strains are the most common (7.35 per club per season) followed by knee injuries (4.75 per club per season). Other common injury sites over the last decade include ankle (3.55 per club per season), hip and groin (3.30 per club per season), head (2.98 per club per season), foot (2.66 per club per season), calf (2.47 per club per season), shoulder (2.20 per club per season), quadriceps (1.66 per club per season), and lower back (1.41 per club per season) (McCaskie et al., 2021). Injury incidence in the NRL is measured per 1000 hours compared to a number of injuries per club per season. Total injury incidence of 89.2 per 1000 hours was reported (in or across how many years), with lower limb injuries constituting the majority (54.3 per 1000 hours) (King et al., 2022). Total injury incidence in the NRL has reduced from 2014 (147.6 per 1000 hours) to 2021 (89.2 per 1000 hours) and compared to the AFL the biggest difference is a higher incidence of head and neck injuries (14.9 per 1000 hours) (King et al., 2022).

Injury prevalence is defined as the number of missed matches per club per season with knee (35.38) and hamstring strain injuries (28.03) the largest contributors for missed matches in the AFL (McCaskie et al., 2021). Specifically, ACL injuries (15.11 missed matches per injury) and posterior cruciate ligament (PCL) injuries (5.18 missed matches per injury) are the knee injuries with the highest severity (McCaskie et al., 2021). Hamstring strain injuries are less severe (3.0 matches missed per injury) but the high incidence rates cause them to have the second highest prevalence among all injuries. Foot injuries (18.08 missed matches per club and season), ankle injuries (15.63 missed matches per club per season), and hip and groin injuries (11.27 missed matches per club per season) are other injury types that are responsible for longer time loss among players (McCaskie et al., 2021). The most common injuries in the NRL are head injuries (16.8 per 1000 hours), knee ligament injuries (10.8 per 1000 hours), upper leg injuries (5.5 per 1000 hours), arm injuries (4.3 per 1000 hours), shoulder injuries (4.1 per 1000 hours), and lower leg injuries (2.7 per 1000 hours) (NRL, 2020). Concussions (91 matches missed per club per season) are the most prevalent injuries in the NRL followed by hamstring strains (41 matches missed per club per season), calf (26 matches missed per club per season), medial collateral ligament (MCL) (21 matches missed per club per season), ACL (15 matches missed per club per season), PCL (10 matches missed per club per season), and tibiofibular (20 matches missed per club per season). Despite differences in physical demands of the sports the incidence, prevalence and severity of the most common lower limb injuries is comparable between both the AFL and NRL.

2.4. Anatomy and Biomechanics of the Lumbar Multifidus

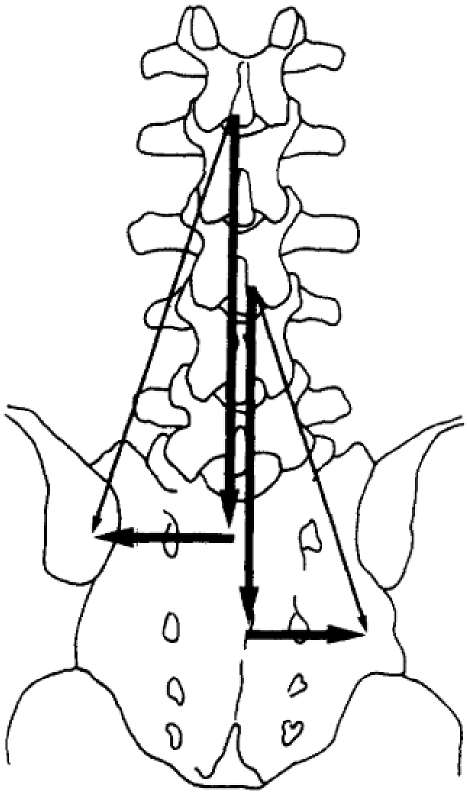
The lumbar multifidus is the largest muscle across the lumbosacral joint and the most medial of the lumbar back muscles, (Figure 4) divided into five separate bands (Kay, 2001; Macintosh & Bogduk, 1986; Macintosh et al., 1986). It can be classified as a spino-transverse muscle that is responsible for trunk extension, contralateral rotation, and lateral flexion based on cadaveric data and plotting of the muscle insertion lines (Bogduk et al., 1992b). When viewed in the coronal plane, the lumbar multifidus produces a force that can be divided into horizontal and vertical components, with the vertical component accounting for 71% of the total force produced (Figure 5). Caudal attachments of the lumbar multifidus are located almost directly below its origins on the spinous process, leading to the vertical force being produced perpendicular to the spinous process. The lumbar multifidus induces posterior rotation of the vertebrae of origin and is less capable at producing posterior shear forces. The lumbar multifidus only contributes to the rotary component of trunk extension and has no influence on posterior translation.

Figure 4: The component fascicles of the lumbar multifidus (A) The laminar fibres of the lumbar multifidus (B-F) The fascicles from the L1-L5 spinous processes, respectively (Bogduk, 2012)



Electromyographic (EMG) studies on the lumbar multifidus showed that the muscle is most active during contralateral rotation of the trunk in a standing position (Morris et al., 1962b) and during erect sitting and during resisted sitting rotation (Bengt Jonsson, 1970). Morris et al. (1962b) used fine wire electrodes in five healthy male participants investigating the activity during standing tasks with the lumbar multifidus showing the highest electrical activity during standing trunk extension from a 90-degree flexed position, hyperextension of the trunk, contralateral rotation towards the end of the range of motion and contralateral flexion of the trunk. Bengt Jonsson (1970) investigated electromyographical activities during standardised tasks in 13 healthy adults using wired electrodes inserted in spinal muscled from levels T12 to L5. Notably, in this study the lumbar multifidus displayed different activation patterns at level L5 depending on the medial and lateral insertion of the electrode. Electrode position was verified after the testing procedure using carbon dioxide. Both the iliocostalis and longissimus also showed differences in their functions at the same level. Both studies are limited by low participant numbers and their age but are still considered to be high quality evidence in a more recent review (Kay, 2001).

Figure 5: The resolution of the oblique orientation of the fascicles of the lumbar multifidus in a postero-anterior view into major vertical and minor horizontal vectors (Macintosh & Bogduk, 1986)



Activation of selected back muscles in common calisthenics was investigated by Pauly (1966) using fine-wire EMG with one electrode placed in the lumbar multifidus 1cm lateral of the mid-line at height of the posterior superior iliac spine in 20 healthy young males and females. In general, the lumbar multifidus was more active in trunk extension than in flexion tasks with the highest activity of the lumbar multifidus being recorded in a prone arch with arms reaching. In standing tasks like heel raises and standing knee to chest raises the lumbar multifidus was more active than the erector group hypothesised to be required for balance. During a half squat motion with upper limbs reaching forward, activity of the lumbar multifidus increased as the arms started reaching forward and during walking on a treadmill the lumbar multifidus was more active than the erector group. Although all mentioned studies (Bengt Jonsson, 1970; Morris et al., 1962b; Pauly, 1966) are of significant age and are looking at a limited sample size state of the art scientific standards were adhered to.

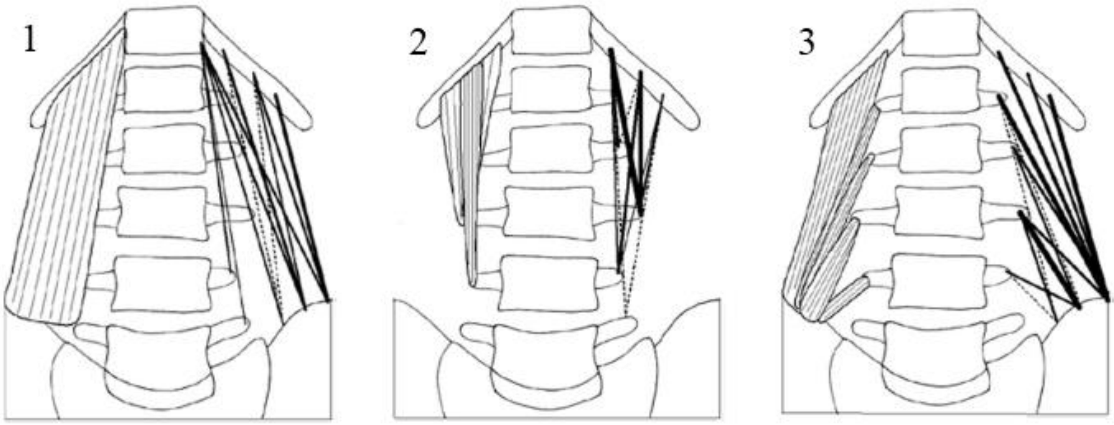
Contributions of the lumbar multifidus to trunk extension and contralateral rotation were shown in EMG studies, but the contributions of the lumbar multifidus to trunk stability are theorised and not yet conclusively proven. Studies investigating the activation of the lumbar multifidus during stabilisation exercises have shown inconclusive results. Vezina and Hubley-Kozey (2000) tested three different stabilisation exercises in 24 healthy male participants with EMG electrodes placed on three abdominal and two paraspinal muscles and concluded that muscular activity during stabilisation exercises was not strong enough to be used as a training stimulus with the eternal obliques being most active (25% MVC) during the anterior pelvic tilt exercise. As a follow-up Hubley-Kozey and Vezina (2002) conducted a similar study in males with lower back pain (LBP) and concluded that stabilisation exercises did not produce enough electrical activation for strengthening of the targeted muscles while Arokoski et al. (2001) concluded, in a study with 24 healthy adults, that electrical activity of the lumbar multifidus could be increased to ~50% of MVC with alterations of trunk positioning during exercises, with females showing significantly ($p < 0.05$) higher levels of lumbar multifidus activation than males.

Trunk extension and rotation do not appear to be the only functions of the lumbar multifidus. A cadaveric study extracting tissue samples from parallel muscles configurations concluded that the lumbar multifidus was dense in muscle spindles (Nitz & Peck, 1986b). This reported density in muscle spindles is believed to facilitate high levels of proprioceptive feedback in the lumbar multifidus which is required to stabilise the lumbar spine which is intrinsically unstable (Panjabi, 1992). Two studies inducing artificial vibration in paraspinal muscles via a vibrating chair concluded that artificial lengthening of the lumbar multifidus caused participants to have a significantly ($p < 0.0001$) weaker repositioning sense of the spine (Brumagne et al., 1999) and that participants suffering from LBP were significantly ($p < 0.0001$) less accurate in repositioning the spine than healthy individuals (Brumagne et al., 2000). The results of these studies are in line with a common theory that the muscular system plays a crucial role in stabilising the lumbar spine (Hodges & Richardson, 1996; O'Sullivan et al., 1997; Wilke et al., 1995) and that LBP impacts the proprioceptive function of the lumbar multifidus (Hides et al., 1996; Hides et al., 1994).

2.5. Anatomy and Biomechanics of the Quadratus Lumborum

The quadratus lumborum is located lateral of the lumbar spine and originates from the ilium with insertions at the 12th rib and the lumbar vertebrae (Phillips et al., 2008). Fascicles of the quadratus lumborum are arranged in a frontal, medial and posterior layer (Figure 6) with iliocostal fibres in the anterior layer, lumbocostal fires in the medial layer and iliolumbar and iliocostal fibres in the posterior layer (Phillips et al., 2008). Cadaveric studies found the muscle to have great variability of muscle fibres orientations both between person and within the left and right side of a person (Phillips et al., 2008).

Figure 6: Fascicles of the quadratus lumborum. 1) anterior layer, 2) middle layer, 3) posterior layer. Adapted from Phillips et al. (2008)



The exact function of the quadratus lumborum remains incompletely understood and electromyographic studies found the muscle to contribute to the trunk extension moment during the latter half of the range of motion from erect standing to 90 degrees of hip flexion and simultaneous full forward flexion of a relaxed and kyphotic trunk (Andersson et al., 1996). Short sarcomere lengths of the quadratus lumborum suggest higher force production in an elongated state such as standing trunk flexion (Delp et al., 2001). Furthermore, the quadratus lumborum has demonstrated to be active during contralateral hip flexion in both standing and supine positions as well as walking and upright standing (Andersson et al., 1996). Torque production of the quadratus lumborum is limited due to small and limited fascicles and despite the fascicles being oriented in the coronal plane the muscle only contributes about 10% to lateral trunk flexion torque and compression forces are also about 10 times smaller than those of the erector spinae or lumbar multifidus (Phillips et al., 2008). Due to the costal attachments the quadratus lumborum was suspected to contribute to the respiratory process and it seems to anchor the twelfth rib and to afford a stable base for the diaphragm, but it remains unclear if the muscle has other functions (Phillips et al., 2008).

2.6. Hamstring Strain Injuries

Hamstring strain injuries are characterised by a sudden pain in the posterior thigh where swelling and bruising are possible symptoms with numbness, tingling and distal weakness being rare. To classify as a hamstring strain injury, the pain must occur without direct contact of a foreign body to the hamstring with injuries classified in four grades: Grade 1 (mild): high short inversion time inversion recovery signal that is < 10% cross-section or longitudinal length < 5 cm with < 1 cm fibre disruption, Grade 2 (moderate): high short inversion time inversion recovery signal that is 10-50% cross-section; longitudinal length 5 - 15 cm with < 5 cm fibre disruption, Grade 3 (extensive): high short inversion time inversion recovery signal that is > 50 % cross-section or longitudinal length > 15 cm with > 5 cm fibre disruption and, Grade 4: complete tear (Pollock et al., 2014). Complete tears can cause haematomas, scar tissue and avulsion injuries (Heiderscheit et al., 2010). The majority of hamstring strain injuries (81-83%) are to the biceps femoris muscle and the semitendinosus and semimembranosus muscles are less likely to sustain an injury (Koulouris et al., 2007).

2.6.1. <u>Hamstring Strain Injury Mechanism</u>

Activities common in Australian rules football and rugby league, such as running and kicking, cause the hamstring muscles to undergo lengthening due to simultaneous hip flexion and knee extension. During this lengthening, the mechanical limits of the muscle fibres can be reached or result in an aggregation of microscopic muscle damage (Brockett et al., 2004). Two mechanisms can cause these damages with running-induced injuries occurring during high stress and low strain loading and stretch-induced injuries caused by low stress and high strain actions (Askling et al., 2007). High speed running is the main cause of hamstring strain injuries in elite athletes and the hamstrings are mainly responsible for decelerating the forward swinging shank during the terminal swing phase which generates high loads due to the high momentum of the shank causing a high impulse in the tissue (Yu et al., 2008). Semimembranosus strains are mostly stretch-induced and caused by great strain during lengthening (Askling et al., 2000).

2.6.2. <u>Rehabilitation and Reinjury Risk After Hamstring Strains</u>

After sustaining a hamstring strain injury, players typically go through a period of rest, followed by a progressive exercise programme that aims to gradually increase loading on the musculotendon unit (Heiderscheit et al., 2010; Mendiguchia & Brughelli, 2011). Progression is often based on pain-free thresholds and involves transitioning from low load isometric exercises to eccentric and then sport-specific and explosive movements (Hickey et al., 2017). However, recent studies suggest that introducing loading with tolerable pain early on may lead to greater increases in knee flexor strength and fascicle length and resolve pain earlier than using a pain-free threshold (Hickey et al., 2022; Hickey et al., 2020). The decision to return to sport after a hamstring strain injury is generally based on restoring knee flexor strength, range of motion, and the ability to perform sport-specific movements, such as high-speed running, without pain (Heiderscheit et al., 2010; Mendiguchia & Brughelli, 2011). Generally, athletes tend to return to competition too early increasing the risk of re-injury to the hamstring given biological structures require adequate time to heal (Pieters et al., 2021).

2.7. Knee Ligament Injuries

In Australia the rates of all types of knee injuries have increased in the past 20 years which include, ACL, PCL, MCL and lateral collateral ligament (LCL) injuries, knee dislocations, meniscus tears and knee contusions (Maniar et al., 2022). Any ligament injury is defined as a sprain that can manifest in three grades. Grade 1: the ligament fibres are stretched but no tear is present, Grade 2: incomplete tear of the ligament fibres, Grade 3: complete tear of the ligament fibres. With the high prevalence of ACL injuries in many popular sports, a large focus in sports medical research lies on preventing these injuries.

2.7.1. <u>Mechanism of ACL Injury</u>

Due to the knee joint's ability to move in all three anatomical planes (sagittal, frontal, and transverse) ACL injuries tend to have complicated underlying mechanisms.

The ACL stabilises the knee joint by preventing excessive anterior motion of the tibia and limiting rotational knee movements (Butler et al., 1980; Duthon et al., 2006; Markolf et al., 1995). It can be assumed that most ACL injuries occur during multi planar movements (Quatman et al., 2010) where translations and rotations in different planes happens simultaneously. Non-contact ACL injuries constitute the majority of injuries sustained in Australian rules football with video analysis suggesting the main mechanism being a combined valgus and internal rotation during unanticipated change of direction (Cochrane et al., 2007). Injuries to the ACL are often observed during an "inward collapse" of the knee when the joint is between 10 and 30 degrees of flexion with the foot landing flat and the trunk being in lateral flexion (Hewett et al., 2009). Landing and regaining balance can cause the knee to experience either a varus or valgus moment combined with external rotation and are thus less likely to cause an ACL injury (Cochrane et al., 2007). Increased valgus moment in the knee is theorised to be the main cause for an ACL injury (Ueno et al., 2020) and has been examined during cadaveric studies based on anatomical features of the knee (Markolf et al., 1995) and in-vitro simulations of ACL strain (Bates et al., 2019). Biomechanical laboratory studies found higher valgus moment during sidestepping than straight running or crossover cutting (Besier, Lloyd, Ackland, et al., 2001; Besier, Lloyd, Cochrane, et al., 2001) and that any deacceleration in the lead up to the sports manoeuvre increases the likelihood of sustaining an injury, especially in conjunction with knee extension.

2.7.2. <u>Rehabilitation and Reinjury Risk After ACL Injury</u>

Any injury to the ACL requires extensive rehabilitation and results in lengthy periods of time lost from playing sports (Webster et al., 2021). The earliest reported return to football activity was four months in exceptional circumstances but players often miss up to 12 months and an average of 21.5 matches (Lai et al., 2018). Surgical reconstruction of the torn ACL is by far the most common method of treatment (Lai et al., 2018) but non-surgical treatment options are available (Filbay & Grindem, 2019). The goal of surgery is to restore stability to the knee joint, enable a return to sports or daily activities, and minimise the risk of long-term knee joint degeneration (Filbay & Grindem, 2019) but many athletes continue to experience long-term knee dysfunction and an increased likelihood of developing knee osteoarthritis (Bodkin et al., 2020). The majority of elite Australian football players (74-77%) return to play at the highest level and 71% of players that sustained multiple ACL injuries achieve a return to play (Lai et al., 2018). At a sub-elite level, a significantly lower proportion (42%) achieve a return to play to their pre-injury level (Ardern et al., 2011). Certain factors limit the successful return to play of football players. For example, an ACL injury to the dominant side of an athlete reduced their chances to return to their competition level and similar to general ACL injury risk, increased body mass also reduces the chances of a successful return to play (Liptak & Angel, 2017). Generally, players over 30 years old were less likely to return to play (Liptak & Angel, 2017) but players with an experience of over 50 AFL matches had a higher chance of returning to play in the AFL (Lai et al., 2018). Players that were drafted either in the first round or as a priority were also more likely to return to play in the AFL, a finding that is consistent with other professional leagues like the American National Football League (Shah et al., 2010).

Physical deficiencies often persist after an ACL injury with athletes having lower knee flexor strength (Konrath et al., 2016), lower knee extensor and flexor rates of force development (Turpeinen et al., 2020), altered knee joint kinematics and kinetics during walking, running, jumping, and landing (Krafft et al., 2020; Moore et al., 2020), and greater between-leg asymmetries in countermovement jump force profiles (Baumgart et al., 2017; Read et al., 2020) compared to uninjured players.

2.8. Injury Risk Analysis and Modelling

The main aim of research into injury risk in athletes is to reduce the number of injuries occurring during match play and training and the framework by (van Mechelen et al., 1992) provides a scientific basis for this process (Figure 1). In the literature the focus often lies on establishing the extent of sports injuries and finding risk factors for common injuries. An update to the described framework by Finch (2006) added two additional steps to the process first testing the preventative measures under ideal conditions (e.g., a laboratory study) and afterwards disseminating it to the "real world" but conceptually keeps the methodological approach consistent with van Mechelen et al. (1992).

Many publications have established the extent of the problem and attempted to find risk factors that are either of causal nature or based on association (Stovitz et al., 2019). Transitioning to the third step usually involves exercise programmes targeted to change previously identified modifiable risk factors (Taylor et al., 2015; Wing & Bishop, 2020) by aiming to strengthen targeted muscle groups. Different exercise programmes have shown the capacity to decrease non-contact ACL injuries (Taylor et al., 2015; Webster & Hewett, 2018) in select populations with less successful interventional studies reported for hamstring strain injuries (Opar et al., 2021). Overall, the issue remains that incidence rates of hamstring strain injuries remained stable in Australia (McCaskie et al., 2021) while ACL injuries are steadily increasing (Zbrojkiewicz et al., 2018) leading to the conclusion that the current approach of preventing non-contact lower limb injuries is either not working as intended or that effective injury prevention programmes are not disseminated widely enough to have widespread impact.

2.8.1. *Statistical Modelling of Injury Risk*

To quantify injury risk in athletes, statistical methods can be used that rely on a classification of players based on the occurrence or absence of an injury in relation to a pre-defined risk factor. The outcome of this classification can be one of four categories (Ruddy et al., 2019):

1. True positive (TP) = the variable of interest was present, and the athlete was injured.
2. False positive (FP) = the variable of interest was present, but the athlete avoided injury.
3. True negative (TN) = the variable of interest was absent, and the athlete avoided injury.
4. False negative (FN) = the variable of interest was absent, but the athlete was injured.

Those four classifications are used to calculate the risk associated with a specific factor and multiple methods are common. The probability of sustaining an injury can be expressed as a number between zero and one or expressed as percentages where the zero represents no chance of sustaining an injury and the one representing a certain injury occurrence (Grimes & Schulz, 2008). Probability can be calculated as follows:

$$Probability = \frac{TP + FN}{TP + FP + FN + TN}$$

In contrast to probability the odds of an event happening is the ratio of the likelihood of an injury occurring against the likelihood of an injury not occurring (Grimes & Schulz, 2008) and is calculated as below:

$$Odds = \frac{TP + FN}{FP + TN}$$

Usually in sports medicine publications either relative risk or odds ratios are expressed to quantify a risk factors association with an injury and both these build on the concepts established above. Relative risk is the ratio of the probability of sustaining an injury in the group where the risk factor is present over the probability of an injury in the group where the risk factor was not present (Schmidt & Kohlmann, 2008):

$$Relative\ risk = \frac{\frac{TP}{TP + FP}}{\frac{FN}{FN + TN}}$$

Conversely odds ratios represent the odds of an injury occurring the group where the risk factor is present over the odds of an injury occurring in a group where the risk factor is not present (Schmidt & Kohlmann, 2008):

$$Odds\ ratio = \frac{\frac{TP}{FN}}{\frac{FP}{TN}}$$

All previous calculations only work on the basis that risk factors are either present or not present (dichotomous) in an individual, but risk factors can also be continuous variables (e.g., age or body mass) associated with an increased risk of sustaining an injury. Two options remain on handling continuous variables exist: 1) a cut-off point for the variable can be defined and participants classified according to being either above or below this point to convert a continuous variable into a dichotomous variable or 2) using a logistic regression model. A logistic regression model has the capacity to not only handle continuous variables but can also take multiple independent variables in relation to one dichotomous (Injured vs not injured) outcome variable (Sperandei, 2014). The logistic regression model is defined as

$$\log\left(\frac{Probability}{1 - Probability}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_m x_m$$

with β_i being the regression coefficients for the reference group and x_i being the independent variables (Sperandei, 2014). To evaluate the ability of any method to estimate the risk associated with a factor the sensitivity and specificity of the prediction can be calculated. Sensitivity refers to the ability of the predictive variable to correctly identify individuals at risk of injury (Akobeng, 2007):

$$Sensitivity = \frac{TP}{TP + FN}$$

and specificity measures the ability to correctly classify individuals that are not at risk of injury (Akobeng, 2007):

$$Specificity = \frac{TN}{TN + FP}$$

Together sensitivity and specificity can be interpreted as receiver operator characteristics where the sensitivity at every point is plotted against the 1 - specificity shaping a curve and the area under the curve can be interpreted as a general measure of the predictive ability of a risk factor (Mandrekar, 2010). The area under the curve will always lie between zero and one where zero shows an inability to predict the outcome and one represents a perfect prediction without any misclassifications. Therefore, an area under the curve of 0.5 would correspond to a prediction that is accurate in 50% of cases requiring an area under the curve of at least 0.75 to be classified as a “good” predictor (Mandrekar, 2010).

Investigating injury risk inherently comes with some the assumption that complex non-linear interactions will be simplified into a finite number of variables which always leads to a loss of information (Ruddy et al., 2019). Even multivariable approaches that are now common in the literature only manage to capture a small frame of the whole picture (Bittencourt et al., 2016) but are generally recommended over univariable approaches (Mendiguchia et al., 2012). Using a univariable approach assumes that the complete injury risk can be broken up into individual components and that the risk of each individual component will add up to the complete injury risk but fails to take non-linear interactions into account (Mendiguchia et al., 2012). Even multivariable studies that try to control for as many confounding variables as possible can only account for a limited proportion of the total injury risk (Timmins et al., 2016). Modern machine learning approaches are able to handle increased complexity and are a step towards more complexity and away from reduction (Bittencourt et al., 2016; Ruddy et al., 2019).

2.8.2. Risk Factors for Hamstring Strain Injuries

Due to the high incidence rates of hamstring strain injuries many publications are investigating injury risk factors. Consistently only older age, previous hamstring strain injury, previous ACL rupture, and previous calf strain injury could be confirmed as risk factors for subsequent hamstring strain injuries (Green et al., 2020). Various modifiable factors have been explored to identify their association with hamstring strain injuries, including hamstring muscle strength and flexibility (Green et al., 2020). Different methods have been used to measure knee flexor strength, such as isokinetic dynamometry and force measurement during the Nordic hamstring exercise (Opar et al., 2013). Isokinetic testing allows the evaluation of concentric and eccentric strength at various joint velocities and is usually performed for both the quadriceps and hamstrings to determine an agonist-antagonist strength ratio (van Dyk et al., 2016). Nonetheless, studies suggest that isokinetic knee flexor tests do not appear to increase the risk of hamstring injury (Green et al., 2020; van Dyk et al., 2017). Meanwhile, assessing eccentric knee flexor strength during the Nordic hamstring exercise has shown mixed results, with some studies finding lower force and greater between-leg imbalances in Nordic eccentric knee flexor strength as risk factors for future hamstring strain injury, while others have found no association (Opar et al., 2021). Knee flexor strength may be a mediating factor, with low Nordic eccentric knee flexor strength and short biceps femoris fascicle length increasing the risk of future hamstring strain injury while also reducing the injury risk associated with non-modifiable risk factors like age and prior injury (Timmins et al., 2016). In contrast, knee joint flexibility, mobility, and range of motion have been shown to have little to no association with hamstring strain injury risk (Green et al., 2020). Additionally, the number of hamstring strain injuries increases towards the end of a match suggesting that fatigue influences injury risk (Ekstrand et al., 2011; Woods et al., 2004).

2.8.3. ACL Injury Risk Factors

Previous ACL injury remains the strongest predictor for reinjuring the ACL graft in the same knee (Orchard et al., 2001) and also sustaining a subsequent injury to the contralateral knee (Walden et al., 2006). Many other modifiable and non-modifiable risk factors for ACL injuries have been identified over the years and summarised in systematic reviews (Pfeifer et al., 2018; Smith et al., 2012a, 2012b). In addition to previous ACL injury the non-modifiable risk factor age also has consistently demonstrated associations with ACL injury risk with young adults (age 20-24) having the highest incidence of ACL tears (Zbrojkiewicz et al., 2018). Female athletes are more likely to sustain an ACL injury than male athletes with many potential factors such as hormonal changes during the menstrual cycle or use of contraceptive pill (Möller-Nielsen & Hammar, 1989), differences knee morphology (Scerpella Tamara et al., 2005; Wojtys et al., 2003), weaker mechanical properties of the ACL (Anderson et al., 2001; Chandrashekar et al., 2006; Chandrashekar et al., 2005), athletic training status, and kinematic differences (Chappell et al., 2007). Genetics of the individual can also be a non-modifiable risk factor for sustaining an ACL tear and genetic predisposition increasing ACL injury risk seems to exist (Flynn et al., 2005).

The number of ACL injuries in Australia has been increasing over the last years while it remained steady in other western countries (Maniar et al., 2022). Geographic location can be considered an extrinsic non-modifiable risk factor for ACL injuries and countries with warmer climates consistently have higher incidence rates potentially due to higher friction of the playing surface in warmer weather (Orchard, Walden, et al., 2013).

Many modifiable risk factors for ACL injuries exist starting with above average body mass or body mass index (BMI) (Uhorchak et al., 2003). Muscular strength deficits in the hip abductors and external rotators could be identified as potential risk factors for ACL injuries (Khayambashi et al., 2016) and impaired reflex control of the trunk was a predictor for ACL injuries in female collegiate athletes (Zazulak et al., 2007a). Athletes that showed a valgus position during landing at higher risk of sustaining an ACL injury and certain tibial movements caused increased strain in the ACL (Quatman et al., 2011). Lower hip internal and external rotation range of motion were also suggested to increase ACL injury risk (Tainaka et al., 2014).

2.9. Lumbar Muscle Morphology as a Risk Factor for Lower Limb Injuries

Recently muscle size of some lumbar muscles has been suggested to be a modifiable risk factor for lower limb injuries in team sports. A study by Hides et al. (2011) found significant differences between lumbar multifidus cross-sectional area of AFL players that missed four or more training sessions due to a hip, groin or thigh injury compared to players that missed fewer training sessions. Only data from one AFL club was used for this study and only five players missed four or more training sessions due to hip, groin or thigh injuries providing a very limited sample size. Measurements of lumbar muscle morphology in Hides et al. (2011) were carried out by magnetic resonance imaging and for the statistical analysis only a between group comparison was used lacking a quantifiable estimation of injury risk. To address the issues regarding a small sample size Hides et al. (2014) carried out a follow-up study including six professional AFL clubs with 261 players which remains the largest study in the field to date. Medical imaging was carried out using ultrasound which has been proven to be a valid (Hides et al., 1995) and reliable (Fortin et al., 2021) tool that allows for faster processing times making larger sample sizes feasible and was established as the most consistently used measurement method. Additionally, the statistical approach was shifted to a regression model finding that players with a smaller lumbar multifidus were at higher risk (odds ratio (OR)=1.43 per cm^2 below the mean, 95%CI=1.14-1.82) of sustaining a lower limb injury during the playing season (Hides et al., 2014). The analysis was shifted towards pooling all lower limb injuries in contrast of focussing on hip, groin and thigh injuries mixing different injury mechanisms (Hides et al., 2014).

Continuing from the previous study Hides and Stanton (2017) found that cross sectional area of the lumbar multifidus in conjunction with cross sectional area of the quadratus lumborum showed a stronger association with lower limb injury risk during the playing season. Players that had a smaller lumbar multifidus than quadratus lumborum were at higher risk of sustaining an injury during the playing season (OR=5.29, 95%CI= 1.49-18.52) and preseason (OR=14.71, 95%CI= 2.16-99.0) but smaller lumbar multifidus (OR=2.08, 95%CI= 1.23-3.51) and larger quadratus lumborum (OR=2.12, 95%CI= 1.18-3.81) were significantly associated with preseason lower limb injury risk as well. This investigation was based on a subgroup of players who participated in the previous study by Hides et al. (2014) with 62 players taking part in preseason testing and 102 players being included from the regular season sample. The odds ratios of sustaining a preseason lower limb injury in this study appear to be very high with large standard deviations (OR=14.71, 95%CI= 2.16-99.0) and would indicate a 14-fold increase in risk of sustaining an injury but no explanation is provided by the researchers as to how these large odds ratios were calculated. The most likely explanation would be the odds ratio's tendency to overestimate common outcomes (Grimes & Schulz, 2008). Conversely odds ratios reported in the following study by Hides et al. (2020) were smaller but still indicated an increased lower limb injury risk for players having a smaller lumbar multifidus (OR=0.42, 95%CI=0.20-0.85) and larger quadratus lumborum (OR=3.52, 95%CI=1.06-11.72). Notably the analysis of injury risk was regarding lumbar multifidus cross-sectional area was flipped with previous studies indicating an increase in injury risk with smaller cross-sectional area and Hides et al. (2020) reported a decrease in injury risk with larger lumbar multifidus cross-sectional area which does not change the interpretation since odds ratios can flipped by taking the inverse (Grimes & Schulz, 2008). The results by this research group indicate promising findings for the usage of lumbar muscle morphology to estimate lower limb injury risk but all studies were carried out in Australian rules football players and require replication in other cohorts to allow for generalisability.

Only a limited number of studies aimed to assess injury risk based on lumbar morphology outside of Australian rules football. A study in South African cricket fast bowlers showed that players sustaining a lower back injury had significantly larger asymmetry between dominant and non-dominant sides of the lumbar multifidus but did not find a significant association with lower limb injuries (Olivier et al., 2017). Similarly, to Hides et al. (2011) the study by Olivier et al. (2017) only used a group comparison and did not employ measurements of injury risk in their analysis. A study performed in North American university rugby league players showed that contractile ability of the lumbar multifidus could also be associated with lower limb injury risk and found that players who showed less thickness change in the lumbar multifidus during an isometric contraction were more likely to sustain a preseason lower limb injury (Roy et al., 2021). Most recently Low et al. (2023) investigated the association between lumbar multifidus size and lower limb injury risk in adolescent rugby union players but did not find a significant association with lower limb injury risk potentially indicating sport specific interactions between lumbar muscle morphology and lower limb injury risk .

The proposed explanation by Hides et al. (2011) was related to the lumbar multifidus' expected role as a component of the trunk stability reflex arc (Nitz & Peck, 1986a) based on a study by (Zazulak et al., 2007a) that indicated higher risk of sustaining an ACL injury in female athletes that had deficits in trunk proprioception. Most notably Zazulak et al. (2007a) only found an interaction in female athletes and not male athletes and there is no clear link in the literature that indicates larger size of a muscle providing better reflex control. The exact mechanism of the interaction remains unclear and there is a possibility that the association found in the reviewed literature is not based on causation (Stovitz et al., 2019). While it does not matter if an association is based on causality or not to estimate injury risk it causes difficulty when interventional studies are trying to modify these risk factors especially if interventions are trying to reduce quadratus lumborum muscle size to reduce injury risk. Muscular function might be an important parameter to measure and force generating capacity of the lumbar multifidus has not been investigated yet.

2.10. Trunk Extension Strength Testing

With the lumbar multifidus and the quadratus lumborum both acting to produce trunk extensor moment a possible way to measure function of these muscles is to assess trunk extension strength. The Sorensen test (Biering-Sorensen, 1984) is a fast and easy procedure that measures trunk extensor muscle endurance, requiring only a plinth and straps. Participants' legs and buttocks are strapped to a plinth with their upper body (from the upper border of the iliac crest) being unsupported and participants are asked to lift their trunk to a horizontal position with the time they manage to maintain this position measured (Biering-

Sorensen, 1984). Participants who were unable to maintain a horizontal position of the trunk for less than 240 seconds (four minutes) were significantly more likely to have a first occurrence of lower back pain in the following year (Biering-Sorensen, 1984). Further studies investigated the reliability of the Sorensen test and consistently found sufficient reliability with a recent systematic review (Martinez-Romero et al., 2020) finding pooled intra-class correlation coefficients (ICC) for inter-rater reliability (ICC=0.94), and intra-rater reliability (ICC=0.88). Assessments of the validity of the Sorensen test concluded that it was an applicable tool to measure trunk extensor muscle fatigue and showed a moderate correlation (r=0.62) between electrical activity (normalised median frequency slope) of the lumbar multifidus and performance in the Sorensen test (Coorevits et al., 2008).

Criticisms of the Sorensen test include the failure to elicit maximal voluntary contraction (MVC) (Keller et al., 2001a), dependency on correct execution with different hip angles showing influences on the results (Champagne et al., 2008), difference between male and female participants (Latimer et al., 1999) potentially based on lower mass of the female upper body, greater lumbar lordosis in females or different muscle composition in females (Demoulin et al., 2006), and the importance of psychological confidence in a time to failure task performance (Applegate et al., 2019). This highlights the importance of correct execution of the Sorensen test and quantification of force production during the test could give additional insights in trunk extensor muscle function.

2.11. Conclusions Form the Literature

This review of the available literature shows that size and function of the lumbar multifidus and quadratus lumborum could be associated with lower limb injury risk in team sports athletes and highlights the limitations that are present in this approach. The majority of the studies suggesting an association between lumbar muscle morphology and lower limb injury risk were done in Australian rules football players and studies in other populations show conflicting results making it necessary to replicate those studies in different populations. So far, most studies investigated lumbar muscle morphology without taking muscular function into account and trunk extension strength testing is a valid method to measure function of the lumbar multifidus and quadratus lumborum. Multiple different mechanisms are present when pooling all lower limb injuries into one analysis making it impossible to differentiate if an association is causal or non-causal highlighting the need for more larger studies that have sufficient sample size to perform subgroup analyses for specific injury types.

Chapter Three

General Methodology

This chapter provides an overview of the used methods to collect data in this thesis. Three distinct data collections were performed over the course of the candidature resulting in four presented chapters.

3.1. Ethics

An ethics application for this project was submitted at the start of the candidature and ethical approval granted by the Griffith University Human Ethics Review Board (GU Ref No: 2019/106). All data collections that involved human participants (chapter four, chapter five, and chapter 6) were performed under the same ethics approval and used the same informed consent form (Appendix 1). All participants provided written, informed consent before volunteering to participate in the respective data collection.

3.2. Ultrasound Imaging

Ultrasound imaging was used to collect any measurements of lumbar muscle morphology throughout the candidature. All images were obtained using B-mode ultrasound (LOGiQ-e, GE Healthcare, Milwaukee, WI) with a 5-MHz curvilinear transducer and imaging acquisition parameters were kept consistent (frequency: 5MHz, gain: 60, depth: 8.0cm) in accordance with prior studies (Hides & Stanton, 2017; Hides et al., 2014; Roy et al., 2021). Participants were asked to lie on a plinth in a prone position with a pillow beneath the abdomen to reduce lumbar lordosis (Wallwork et al., 2007). Ultrasound raters palpated the spinous processes of lumbar (L)2, L3, L4 and L5 and marked them with a black pen. The transducer was oriented in the transverse plane at each lumbar vertebra (L2-L5) to take bilateral images of the lumbar multifidus. To measure the size of the quadratus lumborum, the transducer was moved laterally from L3-4 where the muscle has the largest cross-sectional area (Narici, 1999). Images were saved on a password locked external hard drive after each data collection and backed up on the secure Griffith University research storage space provided to university staff. To calculate the cross-sectional areas of the muscles, outer borders of the muscles were traced manually using the OsiriX software (Lite-version, Pixmeo SARL, Geneva, Switzerland) which then performed the calculations.

3.3. Trunk and Hip Extensor Strength Testing

Following the methodology outlined by Biering-Sorensen (1984) participants were asked to lie prone with the lower body (gluteus maximus, popliteal fold and malleoli) strapped to a plinth and upper body (superior to the iliac crest) hanging over the edge and participants attempted to extend their hips and trunk. The test was modified by using a custom-made harness of 18mm wide nylon slings with a maximum strength rating of 22kn and elastic modulus of ~2.76GPa to connect the participants to a load cell (Vald Performance, Brisbane, Australia, sampling rate = 400Hz) that was fixated to the ground by a custom board and commercially available weight plates. This caused an inability to hyperextend the trunk and to ensure the trunk was horizontal during contraction a spirit level in contact with L5/S1 and C7 was used during a familiarisation contraction.

To measure maximum trunk and hip extensor strength and not only endurance a validated testing protocol was used (Corin et al., 2005) that is comprised of a singular 5s MVIC, 5s rest, followed by a 45s MVIC. Tests were only deemed as acceptable if the force produced at the start of the 45s trial was smaller or the same as the 5s MVIC to ensure maximum effort was given in the first effort. The standard Sorensen test ask participants to maintain a horizontal position of the trunk for four minutes which has been shown to be influenced by psychological factors (Applegate et al., 2019) and only causes submaximal contraction

(Demoulin et al., 2006). The shorter testing procedure aims to address these issues and to standardise trunk extensor strength testing for future investigations (Corin et al., 2005).

Isometric trunk and hip extensor force data was extracted as a comma separated value (csv) file from the software (Valdhub, Vald Performance, Brisbane, Australia) and smoothed using a minimum-order 6Hz lowpass filter with a stopband attenuation of 60 dB and compensation for filter delay in Matlab (The MathWorks, Natick, Massachusetts, USA). Force produced by each participant was normalised based on body weight expressed as N/kg with maximum force produced during the 5s MVIC (maximum strength) and mean force produced during the 45s MVIC (strength endurance) used as the independent variables in the statistical analysis.

3.4. Statistical Analysis

All statistical analyses were performed in R Studio (version 2023.03.0, Boston, US) with specific analysed described in more detail within the study chapters. Descriptive statistics for parametric variables used means and standard deviations while non-parametric variables were described by median and interquartile ranges. Specialised packages (Table 1) were used in accordance with the research question at hand and test assumptions were checked to ensure appropriate usage of the statistical models.

Table 1: R packages used for data analysis, processing, and visualisation.

Package	**Description**	**Version**
metafor	Meta-Analysis Package for R	4.2-0
dplyr	a grammar of data manipulation	1.1.2
readxl	Import excel files into R	1.4.2
mice	Multivariate Imputation by Chained Equations	3.13.0
irr	Various Coefficients of Interrater Reliability and Agreement	0.84.1
blandr	a package to carry out Bland Altman analyses	0.5.1
ggplot2	a system for declaratively creating graphics	3.4.2
ggpubr	functions for creating and customizing ‘ggplot2’- based publication ready plots	0.6.0

Chapter Four

Reliability of Diagnostic Two-Dimensional Ultrasound Imaging to Assess Cross-Sectional Area of the Lumbar Multifidus and Quadratus Lumborum Muscles and Isometric Trunk and Hip Extensor Strength Testing

4.1. Publication Statement

This chapter has been submitted and is under review for publication.

Hajek, M., Roberts L. R., Bourne, M. N., Morris, N. R., Duhig, S. J. (2023). Reliability of diagnostic two-dimensional ultrasound imaging to assess cross sectional area of the lumbar multifidus and quadratus lumborum muscles and isometric trunk and hip extensor strength testing. *Unpublished*

4.1.1. <u>*Contribution*</u>

Martin Hajek's contribution included: study design, data acquisition, analysis, and reporting, interpretation of findings, and writing of the manuscript.

(Signed) [redacted] Date: <u>28/05/2023</u>

Martin Hajek, PhD candidate

(Countersigned) [redacted] Date: <u>28/05/2023</u>

Llion Roberts, Co-principal supervisor

4.2. Preface

Ultrasound imaging is a widely-used non-invasive technology for measuring lumbar muscle size, demonstrating high reliability in multiple investigations (Djordjevic et al., 2014; Mangum et al., 2016; Sanchez Romero et al., 2021; Valentin et al., 2015; Wallwork et al., 2007). Congruently, the Sorensen test (Biering-Sorensen, 1984) is a commonly used tool to measure lumbar muscular strength endurance (Biering-Sorensen, 1984). The first step of this candidature involved developing a modified version of the Sorensen test that aimed to address the test’s limitation regarding its failure to elicit MVIC of the trunk and hip extensor muscles (Keller et al., 2001b) by incorporating a validated 65s protocol (Corin et al., 2005) and quantifying trunk extensor strength by use of a load cell. Subsequently the reliability of the modified Sorensen test was measured, alongside assessing our ability to conduct reliable ultrasound imaging of the region of interest in a population of healthy and recreationally active participants. In order to collect data in a sample of elite athletes it was necessary to have acceptable reliability across variables for both these outcome measures.

4.3. Abstract

BACKGROUND: Previous reliability studies have only investigated lumbar multifidus thickness or change in size during contraction, without assessing the gold standard cross-sectional area or measuring quadratus lumborum size. Although the reliability of the conventional Sorensen test has been examined in numerous studies, the modified version has not yet been investigated.

OBJECTIVES: To evaluate the intra- and inter-rater reliability of ultrasound measurements of lumbar multifidus and quadratus lumborum cross-sectional area, and intra-rater reliability of trunk and hip extensor strength using a modified Sorensen test.

STUDY DESIGN: Repeated-measures reliability study.

METHODS: Intra- and inter-rater reliability for lumbar multifidus and quadratus lumborum cross-sectional area were determined in a sample of 10 healthy and recreationally active participants in two sessions 24 to 48 hours apart. Intra-rater reliability of the modified Sorensen test was assessed using 20 healthy and recreationally active participants in two sessions one week apart. Intraclass correlation coefficients (ICC), coefficients of variation (CV), and 95% minimal detectable change (MDC) and percentages (MDC%) values were calculated for both lumbar multifidus and quadratus lumborum cross-sectional area and trunk and hip extensor maximum strength and strength endurance.

RESULTS: Intra-rater reliability for lumbar multifidus muscle at the fifth lumbar vertebral level (ICC=0.96, CV=1.05%, MDC=0.17cm^2, MDC%=2.3%) and quadratus lumborum cross-sectional area (ICC=0.95, CV=0.8%, MDC=0.09cm^2, MDC%=1.4%) showed excellent reliability. Inter-rater reliability (lumbar multifidus muscle at the fifth lumbar

vertebral level: ICC=0.86, CV=2.24%, MDC=0.35cm^2, MDC%=4.6%; quadratus lumborum: ICC=0.96, CV=1.5%, MDC=0.20cm^2, MDC%=3.2%) were also excellent. Further, reliability for maximum strength (ICC=0.93, CV=6.8%, MDC=0.87N/kg, MDC%=12.1%) and strength endurance (ICC=0.90, CV=8.6%, MDC=0.63N/kg, MDC%=15.4%) from the modified Sorensen test demonstrated excellent results.

CONCLUSION: The employed assessments demonstrated excellent reliability, thus warranting their recommendation to be utilised in future research.

4.4. Introduction

Across an individual’s lifetime, there is a 70-85% probability of experiencing at least one episode of acute low back pain (Negrini et al., 2013). Measuring the size of the lumbar multifidus and assessing of lumbar multifidus strength can provide insights into an individual’s risk of developing lower back pain (Biering-Sorensen, 1984; Wallwork et al., 2009). Further, smaller cross-sectional area of the lumbar multifidus at the fifth lumbar vertebrae and larger cross-sectional area of the quadratus lumborum have been suggested to increase lower limb injury risk in elite football players (Hides et al., 2020).

Ultrasound imaging is a widely-used non-invasive technology for measuring lumbar muscle size, demonstrating high reliability in multiple investigations (Djordjevic et al., 2014; Mangum et al., 2016; Sanchez Romero et al., 2021; Valentin et al., 2015; Wallwork et al., 2007). The most commonly assessed parameter is thickness of the lumbar multifidus in a prone lying position which has demonstrated good reliability in all studies (Djordjevic et al., 2014; Mangum et al., 2016; Valentin et al., 2015; Wallwork et al., 2007). Some investigations also measured the contractile ability of the lumbar multifidus which generally had lower reliability that was still acceptable (Djordjevic et al., 2014; Sanchez Romero et al., 2021; Wallwork et al., 2007), while others assessed lumbar multifidus size in standing, seated or walking positions which only demonstrated fair reliability. (Mangum et al., 2016; Sanchez Romero et al., 2021). One study (Fortin et al., 2021) investigated reliability of measuring lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area and found excellent results. However, no studies have yet assessed the reliability of measuring quadratus lumborum cross-sectional area using ultrasound imaging. A muscle's cross-sectional area informs about the health (Chi-Fishman et al., 2004) and force production potential of a muscle (Maughan et al., 1983).

The Biering-Sorensen test was developed to provide an individual's risk of experiencing acute or chronic low back pain by measuring lumbar muscular strength endurance (Biering-Sorensen, 1984). Although the test has demonstrated good reliability (Keller et al., 2001b; Latimer et al., 1999) and validity for measuring lumbar muscle strength endurance (Coorevits et al., 2008), it has been criticised for not eliciting a maximal voluntary contraction from participants (Keller et al., 2001b), nor eliminating hip extensor involvement (Moreau et al., 2001) . Therefore, suggesting the test should be considered an assessment of trunk and hip extensor strength. Modifying the trunk position also influences the performance and muscular activity during the Sorensen test (Champagne et al., 2008). These indicate that a high degree of standardisation is required to achieve good reliability. Herein, we modified the original Sorensen test to not only assesses trunk and hip extensor strength endurance, but also maximum strength. This modified test involved - in immediate succession - a 5s MVIC, 5s rest, 45s MVIC, 5s rest then a final 5s MVIC (65s total testing time). This protocol can be used in conjunction with a force measuring device, as was undertaken here, to better quantify trunk and hip extensor strength (Corin et al., 2005). This modification to the Sorensen test has not been evaluated previously but could provide a quick and efficient way to gain insight into an individual's trunk and hip extensor strength profile.

Common approaches to quantify the reliability of physiological measures include intraclass-correlation coefficients (ICC), coefficients of variation (CV) and minimal detectable change (MDC) (Atkinson & Nevill, 1998; Weir, 2005). Sources of error include biological variability, instrumentation error, failed compliance by the participant, and rater inaccuracies. Rather than using these parameters in isolation, a combination can help understand the random error associated with any given measure (Atkinson & Nevill, 1998). Derived from an analysis of variance, the ICC indicates whether random error between two groups is similar, and they thus, considered not significantly different (Weir, 2005). Using the ICC is common, and its interpretation is easily standardised, (Koo & Li, 2016) however, it fails to detect systematic errors. Incorporating a t-test reveals whether a systematic difference exists between two groups, while the CV quantifies the change between groups (Atkinson & Nevill, 1998). The MDC can subsequently be used to quantify a measure's sensitivity to change – separating e.g., an intervention-induced change, from measurement variability, thus providing a practical indication for clinicians using the measure in question.

This study has two primary aims: (i) assess the intra- and inter-rater reliability of ultrasound imaging-derived measures of lumbar multifidus muscle at the fifth lumbar vertebral level and quadratus lumborum cross-sectional area, and (ii) asses the between-day intra-rater reliability of a novel modified Sorensen test for assessing hip and trunk extensor strength and endurance in a cohort of healthy, recreationally active participants. By determining the reliability of ultrasound imaging alongside developing a new approach to the Sorensen test, this study aims to provide valuable insights for clinicians, strength and conditioning coaches, and researchers to congruently assess lumbar morphology and strength. These findings may contribute to improving assessments of risk factors for lower back pain and lower limb injuries, promoting the development of evidence-based prevention strategies and informing the design of tailored training programs.

4.5. Methods

4.5.1. Participants and Study Design

This study recruited 10 healthy recreationally active adults for ultrasound imaging and 20 healthy recreationally active adults for isometric trunk and hip extensor strength testing. Participants in the ultrasound imaging arm were assessed on two occasions 24-48 hours apart where they underwent a short (<30 minutes) ultrasound imaging examination. In the trunk and hip extension strength testing arm participants were asked to attend two separate sessions 7 days apart scheduled at the same time and day as the previous week where they performed the same trunk and hip extension strength test. Participants were asked to keep their food intake consistent prior to attending testing sessions and had no history of lower limb injury in the prior 12 months. All participants were given plain language information before providing informed written consent. Ethics approval for this study was granted by the Griffith University Human Ethics Review Board (GU Ref No: 2019/106)

Based on previous investigations of lumbar multifidus muscle at the fifth lumbar vertebral level thickness an ICC of 0.95 (Djordjevic et al., 2014; Wallwork et al., 2007) can be expected when experienced raters are conducting repeated ultrasound measures in a healthy population. A sample size calculation based on the hypothesis testing method described by Walter et al. (1998) using a minimum acceptable reliability of at least "moderate" reliability

(ρ_0=0.61) (Shrout, 1998), expected reliability (ρ=0.95), significance level (α=0.05), desired power (1-β=0.8) and number of repetitions (k=2) in

$$n = 1 + \frac{2k(Z\alpha_{/2} + Z_\beta)^2}{(k-1)\left[ln\left(\frac{1+k\left(\frac{\rho_0}{1-\rho_0}\right)}{1+k\left(\frac{\rho}{1-\rho}\right)}\right)\right]^2}$$

with $Z_{\alpha/2}$ = 1.96 and Z_β = 0.84 giving a required sample size of 8 and requiring 9 participants with an expected dropout of 10% (Borg et al., 2022).

4.5.2. Ultrasound Assessment

Two experienced sonographers conducted ultrasound imaging during the first session for inter-rater comparisons, while one sonographer - the same sonographer in each case - collected images again during a second session conducted 24-48 hours later for intra-rater comparisons. B-mode ultrasound (LOGiQ-e, GE Healthcare, Milwaukee, WI) with a 5-MHz curvilinear transducer acquired images of the lumbar multifidus muscle at the fifth lumbar vertebral level and quadratus lumborum. Imaging parameters were consistent across acquisitions (frequency: 5MHz, gain: 60, depth: 8.0cm).

All ultrasound measurements were collected with participants laying prone on a plinth. The spinous processes of L4 and L5 were palpated and marked with a black pen, positions of the markings were confirmed using ultrasound and corrected if necessary. The transducer was oriented in the transverse plane at each vertebra to measure lumbar multifidus cross-sectional area (Hides et al., 1995). Quadratus lumborum cross-sectional area was measured at L3-L4 where the largest cross-sectional area was demonstrated (Narici, 1999). Images were later assessed offline using OsiriX software (Lite-version, Pixmeo SARL, Geneva, Switzerland). lumbar multifidus muscle thickness was assessed by drawing a line from the tip of the L4/5 zygapophyseal joint up to the superior border of the lumbar multifidus. Outer borders of the muscles were traced manually, and cross-sectional area was calculated. Both raters performed the image tracing for the first session and only one rater performed the tracing for the second session.

4.5.3. *Isometric Trunk and Hip Extensor Strength Testing*

Each participant performed a modified Sorensen test, supporting their upper body (upwards from the iliac crest) in a prone position with the lower body (gluteus maximus, popliteal fold and malleoli) strapped to a plinth. Participants wore a custom-made harness over their upper trunk, with a strap hanging from their xiphoid process and anchored to an immovable object on the floor directly below them (Figure 7). The harness was made from 18mm wide nylon slings with a maximum strength rating of 22kn and elastic modulus of ~2.76GPa. A load cell (Vald Performance, Brisbane, Australia, sampling rate = 400Hz) was fixated between the strap and the immovable object to measure trunk and hip extension force production. A spirit level in contact with L5/S1 and C7 ensured the participants' trunk was horizontal under load. Following a warm-up of three submaximal 5s isometric contractions (50%, 60% and 70% of relative perceived maximal exertion) all participants performed three maximal trunk extension efforts using the protocol of: 5s MVIC, 5s rest, 45s MVIC, 5s rest, 5s MVIC (65s total testing period) (Corin et al., 2005). Participants performed a standardises warm-up consisting of two submaximal contractions (~5/10 RPE) followed by a familiarisation contraction. After 5 min rest participants were asked to perform the fatigue protocol.

Figure 7 Sample assessment of the novel trunk and hip extensor strength test (own photo)

4.5.4. Statistical Analyses

Statistical analyses were conducted in RStudio (Version 2023.03.0, Boston, USA) and load cell data obtained during the trunk and hip extensor strength test were analysed using Matlab (The Math Work, Natick, Massachusetts, USA). Raw data was smoothed using a minimum-order 6Hz lowpass filter with a stopband attenuation of 60 dB and compensation for filter delay. A peak detection algorithm separating the force data to derive the outcome measures (5s MVIC force and 45s mean MVIC force) for each testing session, which were normalised to each participant's body mass and ultrasound imaging outcome measures, including cross-sectional area of the lumbar multifidus muscle at the fifth lumbar vertebral level and quadratus lumborum.

The "irr" package in R (Gamer et al., 2019) was used to calculate two-way single score ICC. Pre-defined categorisations were used to interpret ICC results as poor (ICC < 0.5), moderate (0.5 < ICC < 0.75), good (0.75 < ICC < 0.9) and excellent (ICC > 0.9) with the lower bound of the ICC being used as the main outcome (Koo & Li, 2016).

A two-tailed paired t-test was used to assess systematic bias between the repeated measures, with the null hypothesis being no systematic difference between measures. For each variable in each participant, the CV was calculated as:

$$CV = 100\% * \frac{\sqrt{0.5 * d^2}}{\bar{x}}$$

with *d* being the difference between both testing sessions or raters and mean ($\bar{x}$) being the mean value of all participants (Atkinson & Nevill, 1998). Pervious research established a CV <10% as acceptable reliability if used in conjunction with other measures (Atkinson & Nevill, 1998). Similarly, the MDC was also calculated for each participant as

$$MDC = 1.96 * \sqrt{2} * SEM$$

with the standard error of measurement (SEM) calculated as the square root of the variance and also expressed as a percentage of the mean. Bland-Altman plots, including 95% limits of agreement, were calculated using the "blandr" package (Datta, 2017) and regression plots used to illustrate the raw data.

4.6. Results

4.6.1. Participant Demographics

A cohort of 10 healthy and recreationally active participants (six male, four female) participated in the ultrasound imaging reliability portion. Twenty healthy and recreationally active participants (17 male, three female) volunteered for the isometric trunk and hip extensor strength testing (Table 2).

Table 2: Participant demographics

	Ultrasound imaging	**Trunk and hip extensor strength**
n	10	20
Stature (m)	1.78 (0.08)	1.74 (0.10)
Body mass (kg)	76 (12)	68 (10)
BMI (kg/m^2)	23.70 (2.72)	22.41 (2.07)
Age (years)	26 (4)	26 (2)

Note. Values depict mean and brackets show standard deviation.

4.6.2. Ultrasound Imaging Reliability

Paired t-tests did not show any significant results (Table 3), and thus randomness of errors can be assumed. Intra-rater data for the lumbar multifidus muscle at the fifth lumbar vertebral level (ICC=0.96, CV=1.05%, MDC=0.17cm^2, Figure 8) and quadratus lumborum (ICC=0.95, CV=0.8%, MDC=0.09cm^2, Figure 9) and inter-rater (between sonographer) data (lumbar multifidus muscle at the fifth lumbar vertebral level: ICC=0.86, CV=2.24%, MDC=0.35cm^2, Figure 10; quadratus lumborum: ICC=0.96, CV=1.5%, MDC=0.20cm^2, Figure 11) demonstrated good to excellent reliability. While inter-rater reliability (between tracer) for the lumbar multifidus muscle at the fifth lumbar vertebral level (ICC=0.85, CV= 9.89%, MDC=1.3 cm^2, Figure 12) can still be classified as "good", the between tracer assessment of the quadratus lumborum (ICC=0.63, CV= 9.22%, MDC=0.9 cm^2, Figure 13) only demonstrated moderate reliability.

Table 3: Reliability measures of ultrasound imaging of lumbar muscle cross-sectional area in healthy adults

	LM L5 CSA	**QL CSA**
Intra-Rater		
Mean (SD)	7.49 (0.08) cm^2	6.31 (0.06)
ICC (95% CI)	0.96 (0.88 - 0.99)	0.95 (0.83 – 0.98)
CV	1.0%	0.8%
MDC (%)	0.17 cm^2 (2.3%)	0.09 cm^2 (1.4%)
T-Val (p)	-0.12 (0.90)	0.07 (0.94)
Inter Rater (Same tracer different images)		
Mean (SD)	7.62 (0.18) cm^2	6.19 (0.10) cm^2
ICC (95% CI)	0.86 (0.55 - 0.96)	0.96 (0.87 – 0.99)
CV	2.2%	1.5%
MDC (%)	0.35cm^2 (4.6%)	0.20cm^2 (3.2%)
T-Val (p)	0.54 (0.59)	0.16 (0.88)
Inter Rater		

(Same images, different tracers)		
Mean (SD)	6.95 (0.66) cm^2	5.84 (0.49) cm^2
ICC (95% CI)	0.85 (0.51 - 0.96)	0.63 (0.19 - 0.89)
CV	9.89%	9.22%
MDC (%)	1.30 cm^2 (18.7%)	0.90 cm^2 (15.4%)
T-Val (p)	0.21 (0.41)	0.03 (0.48)

Abbreviations: LM L5=lumbar multifidus at the fifth lumbar vertebrae, QL=quadratus lumborum, CSA=cross-sectional area, CV=coefficient of variation, MDC=minimally detectable change, SD=standard deviation

Figure 8: Bland-Altman (top) and regression plot (bottom) for intra-rater reliability of lumbar multifidus muscle at the fifth lumbar vertebral level

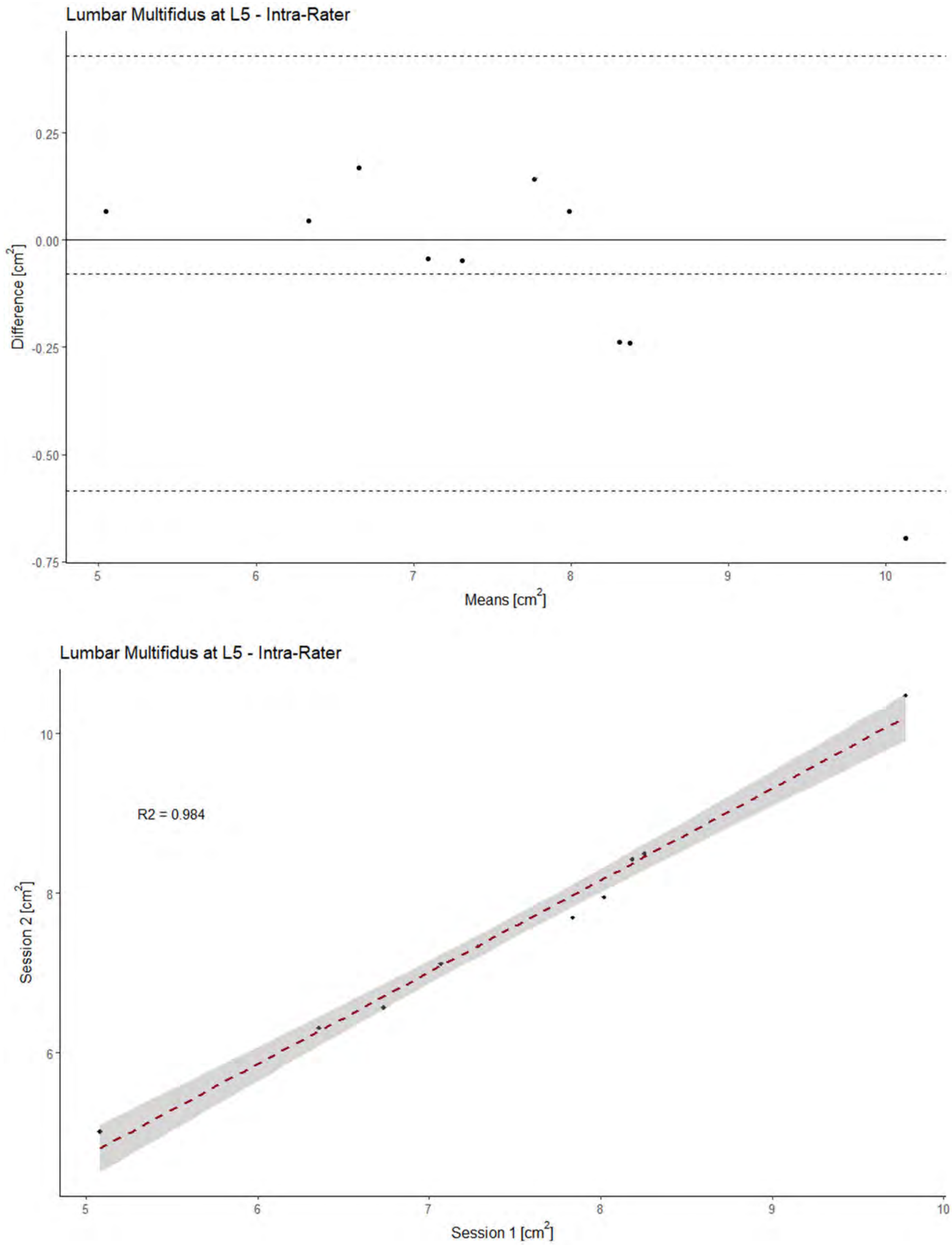


Figure 9: Bland-Altman (top) and regression plot (bottom) for intra-rater reliability of quadratus lumborum

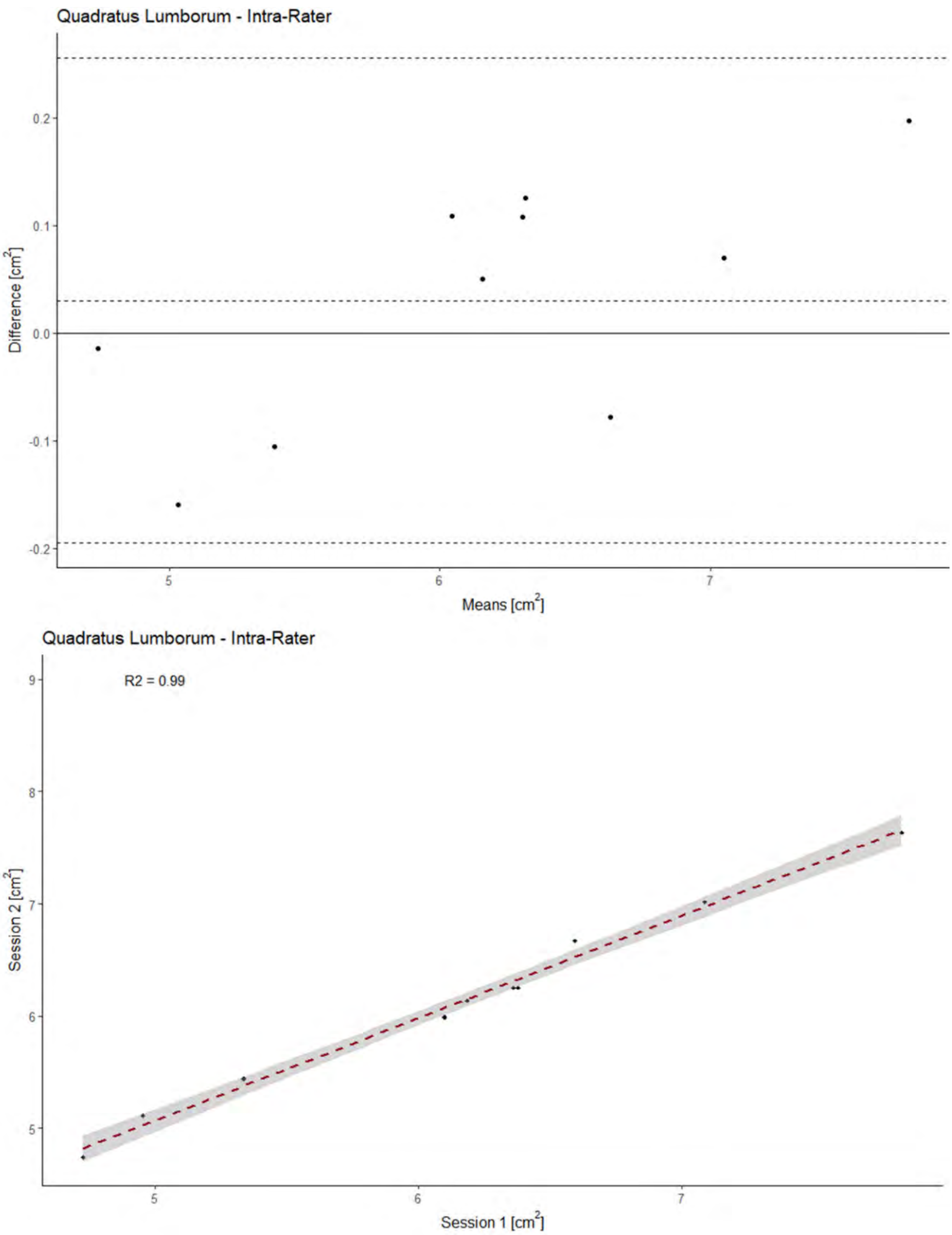
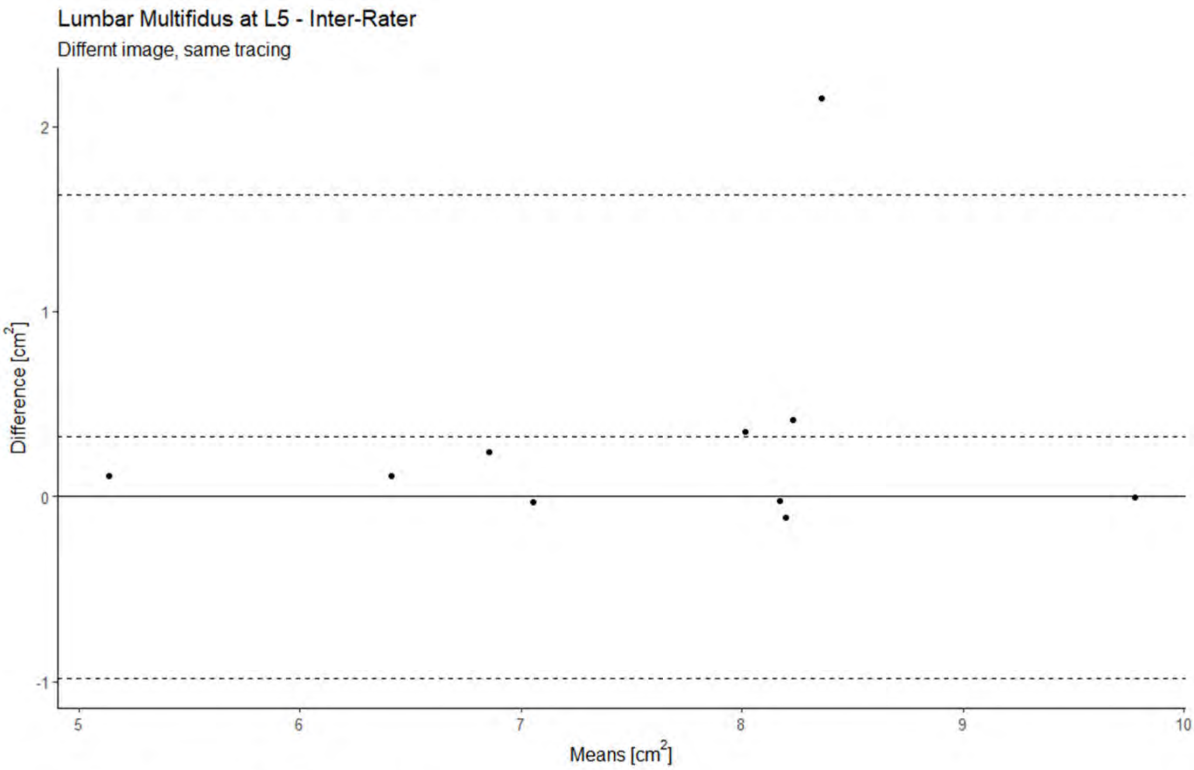


Figure 10: Bland-Altman (top) and regression plot (bottom) for inter-rater reliability of lumbar multifidus muscle at the fifth lumbar vertebral level , when imaging was performed by two sonographers and muscle tracing was performed by one rater.



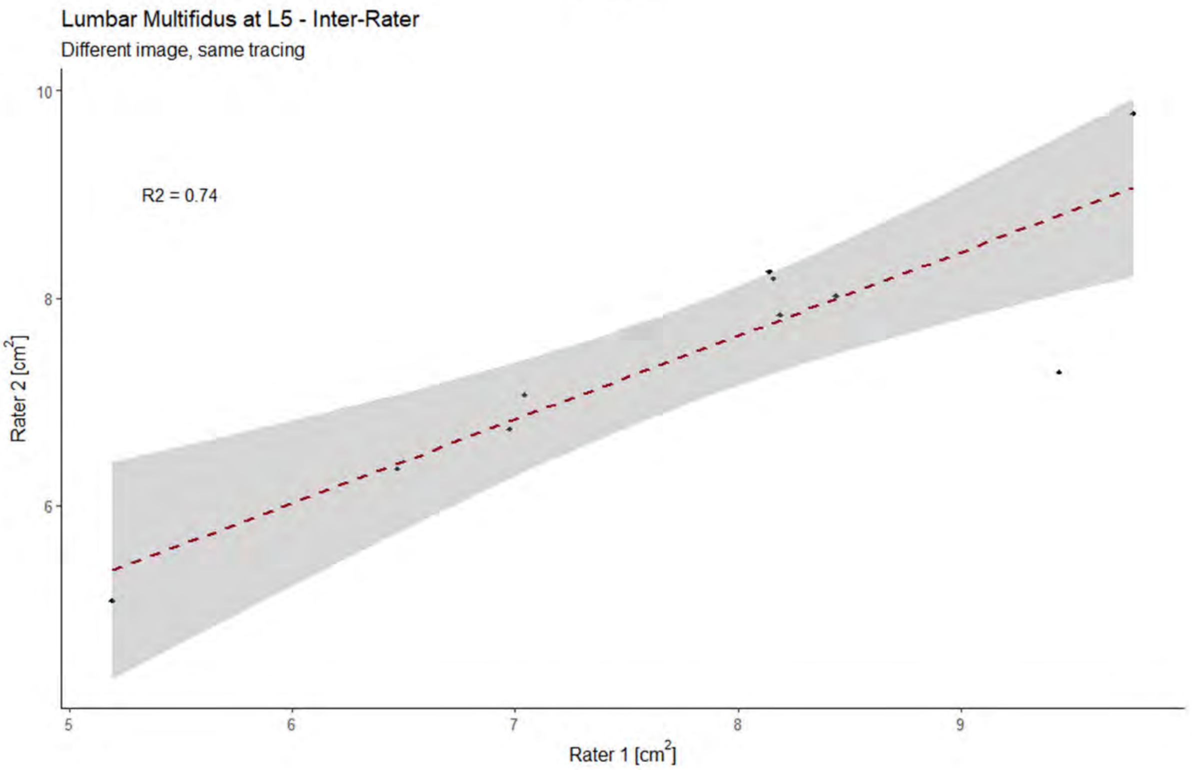
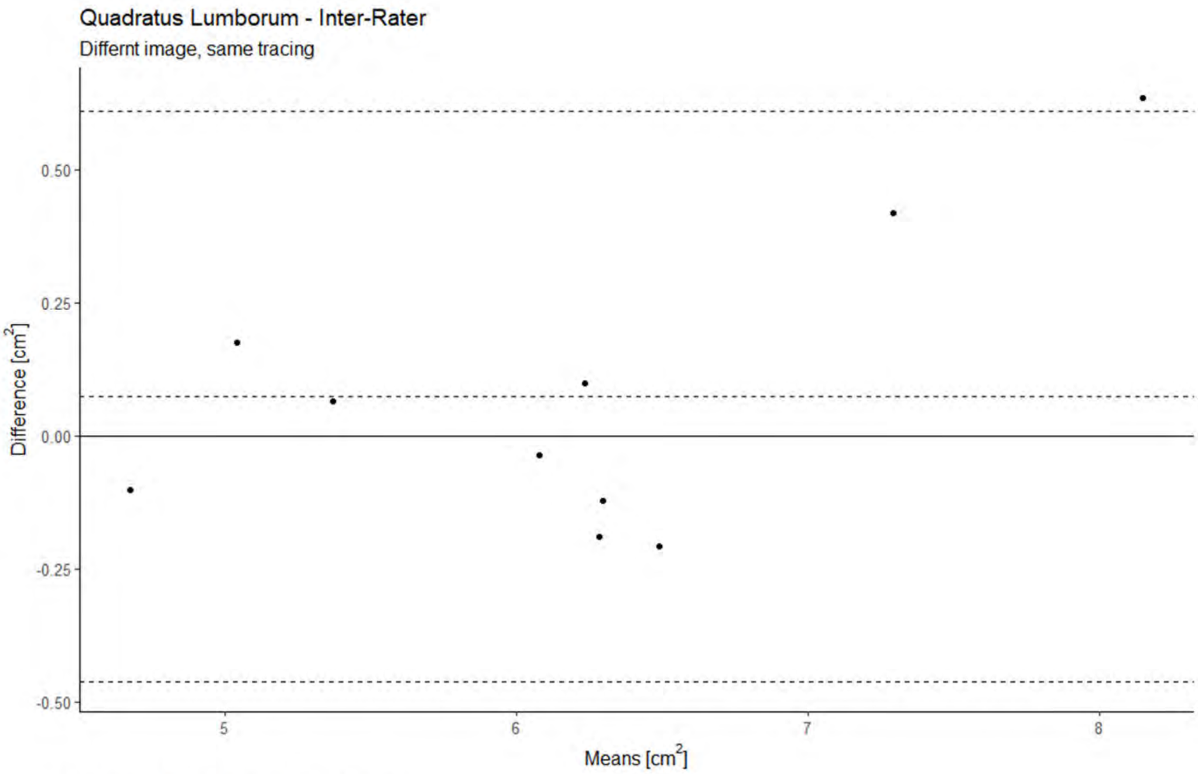


Figure 11: Bland-Altman (top) and regression plot (bottom) for inter-rater reliability of quadratus lumborum, when imaging was performed by two sonographers and muscle tracing was performed by one rater.



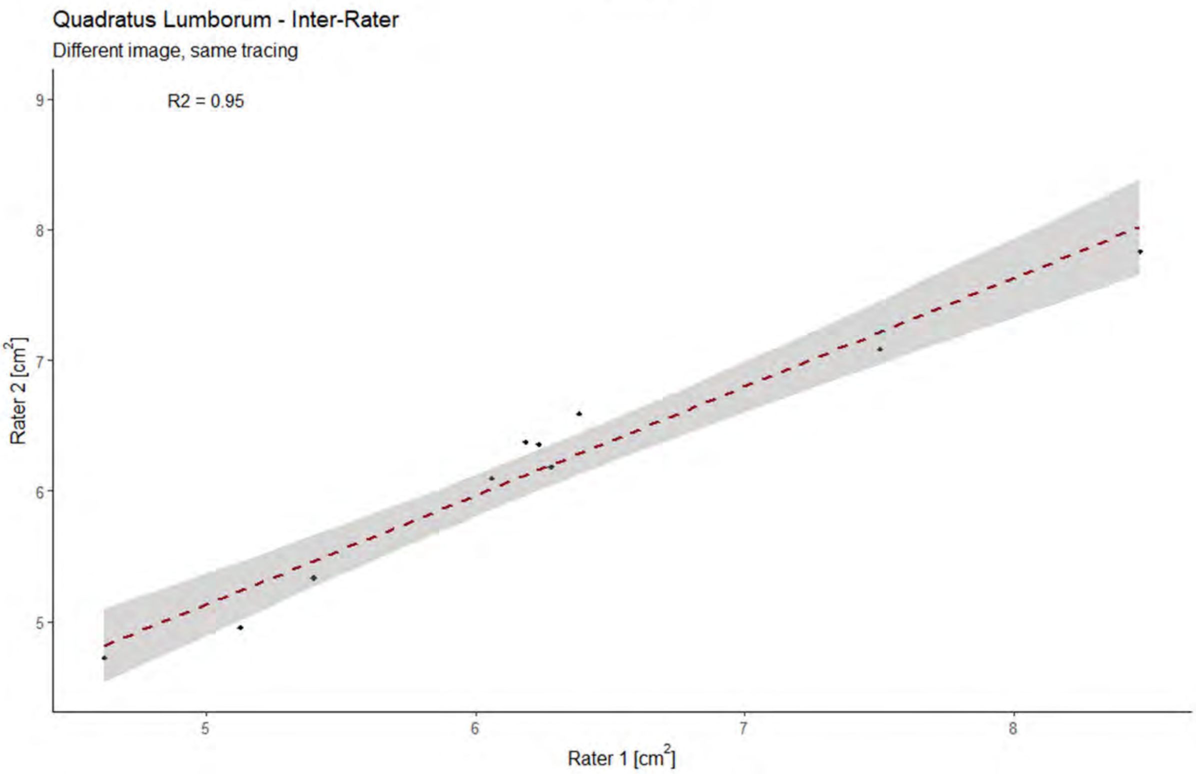


Figure 12: Bland-Altman (top) and regression plot (bottom) for inter-rater reliability of lumbar multifidus muscle at the fifth lumbar vertebral level , when imaging was performed by one sonographers and muscle tracing was performed by two raters.

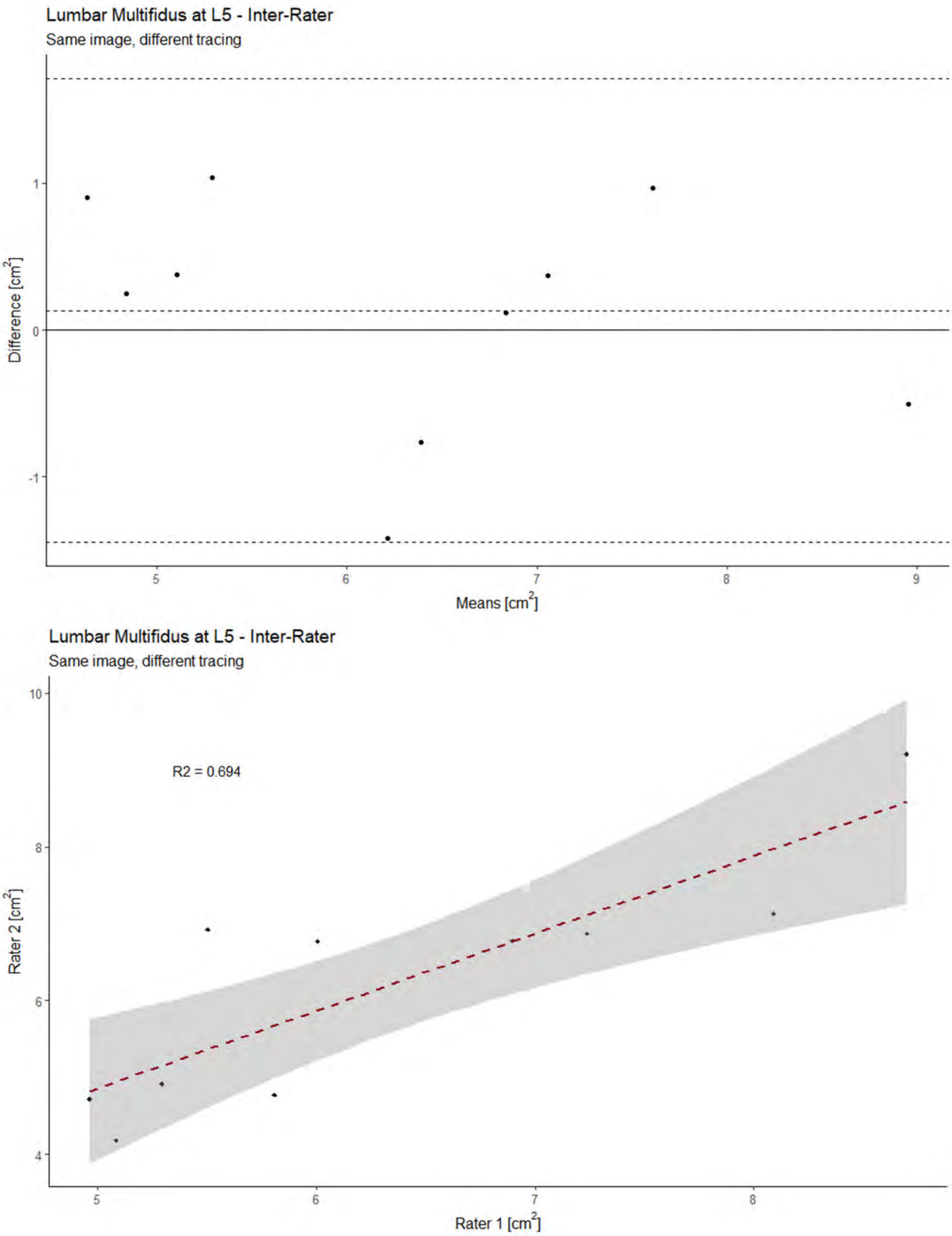
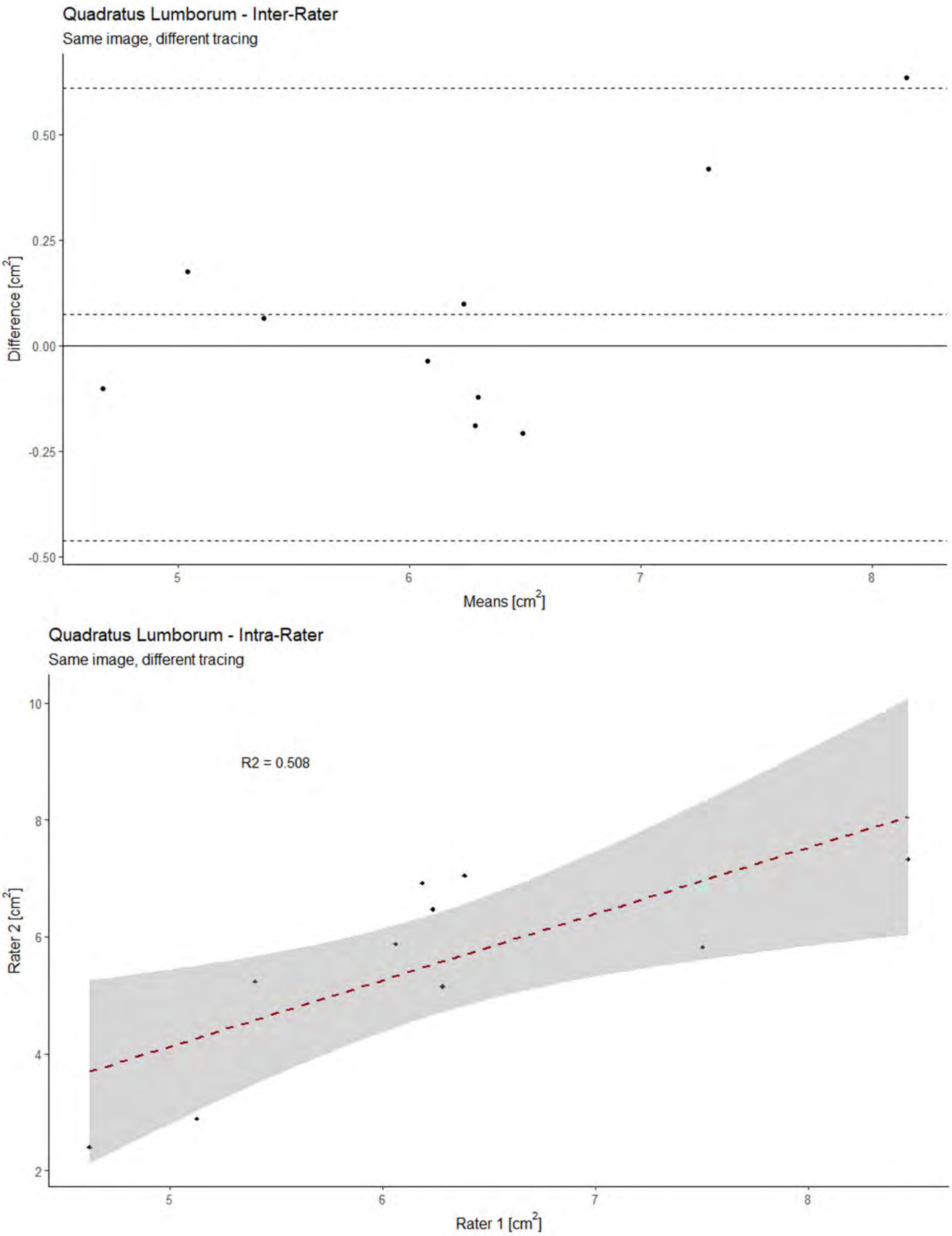


Figure 13: Bland-Altman (top) and regression plot (bottom) for inter-rater reliability of quadratus lumborum, when imaging was performed by one sonographers and muscle tracing was performed by two raters.



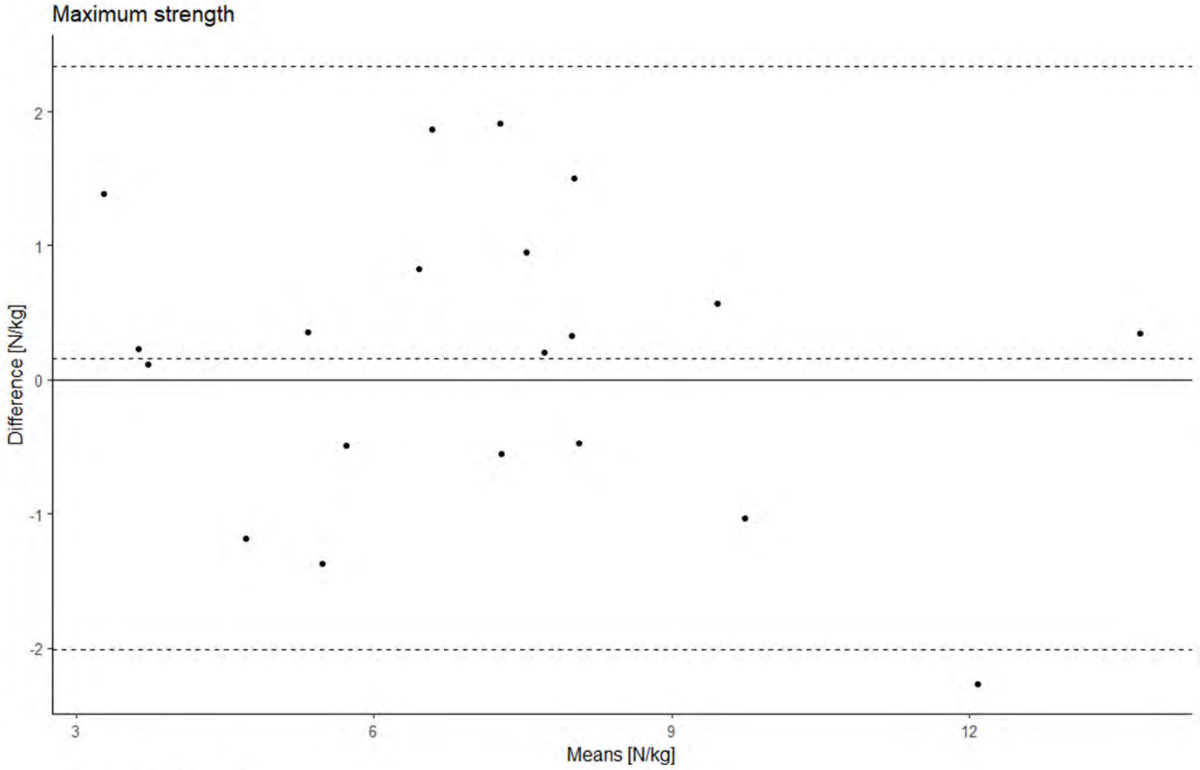
4.6.3. Isometric Trunk and Hip Extensor Strength Testing Reliability

Systematic bias can be excluded due to non-significant findings in the paired t-tests and between day reliability data for maximum strength (ICC=0.93, CV=6.8%, MDC=0.87N/kg) and strength endurance (ICC=0.90, CV=8.6%, MDC=0.63N/kg) showing excellent results to pre-defined standards (Table 4, Figure 14, Figure 15).

Table 4: Reliability measures for trunk and hip extensor strength variables

	Maximum strength	**Strength endurance**
Mean (Std)	7.19 N/kg (0.45)	3.65N/kg (0.32)
ICC	0.93 (0.81-0.96)	0.90 (0.73-0.95)
CV	6.8%	8.6%
MDC (%)	0.87N/kg (12.1%)	0.63N/kg (17.2%)
T-Val (p)	0.18 (0.85)	-0.15 (0.87)

Figure 14: Bland-Altman (top) and regression plot (bottom) for intra-rater reliability of maximum strength



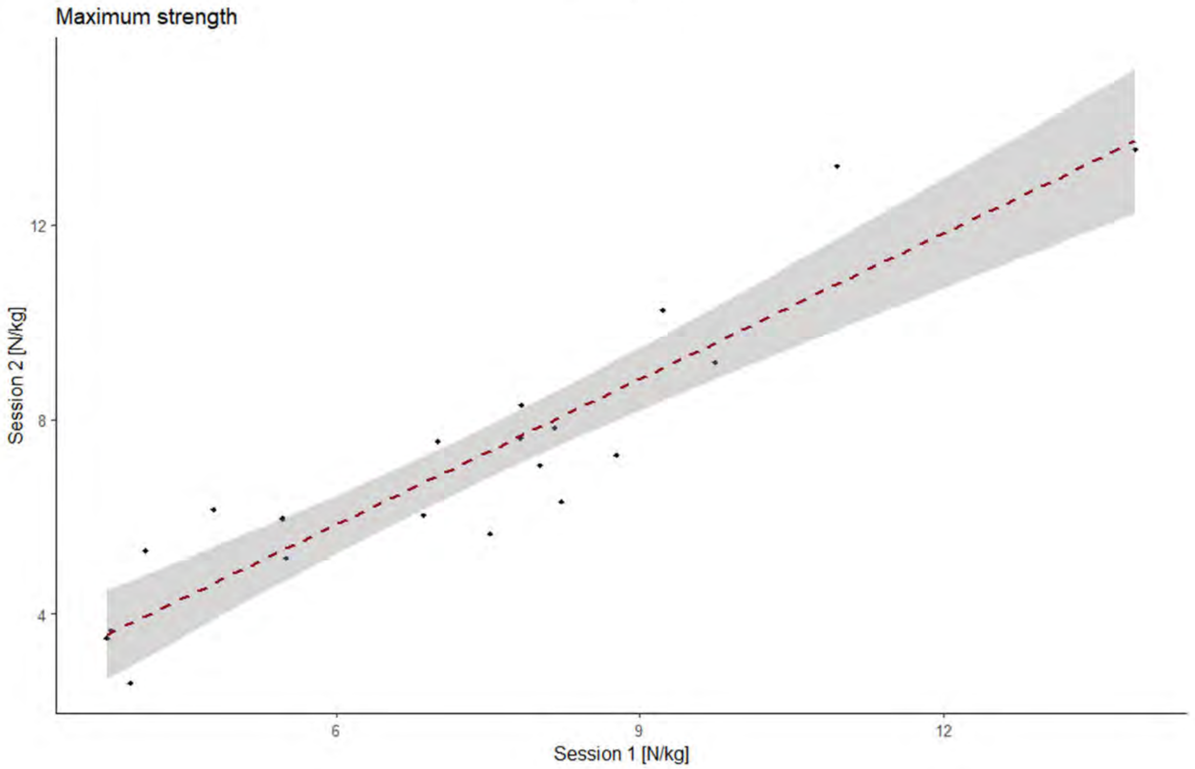
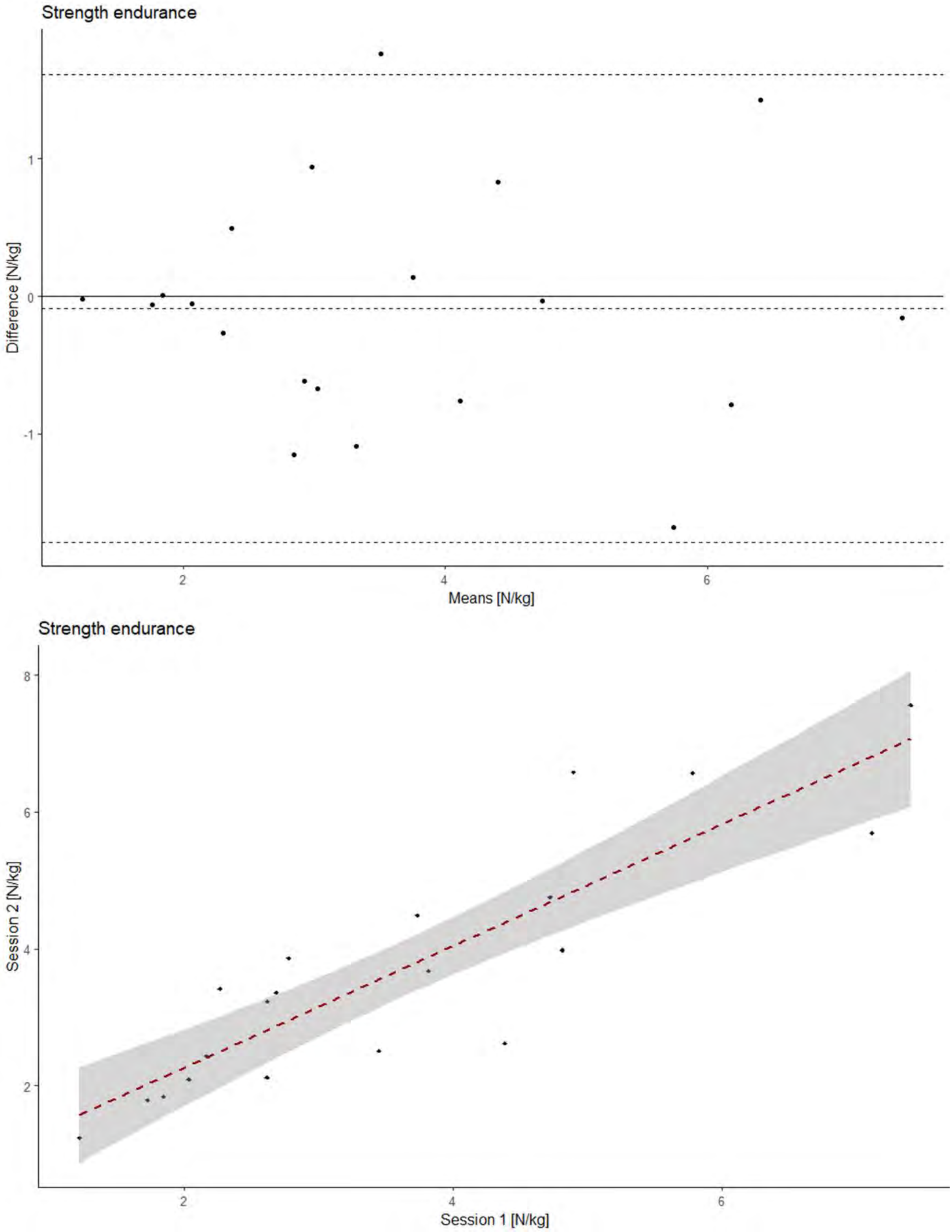


Figure 15: Bland-Altman (top) and regression plot (bottom) for intra-rater reliability of strength endurance



4.7. Discussion

The primary aims of this study were to assess the reliability of ultrasound imaging-derived measures of lumbar muscle morphology, and a novel isometric trunk and hip extension strength test. Our study was the first to assess intra- and inter-rater reliability of cross-sectional area of the quadratus lumborum. The main findings of this study showed “excellent” intra-rater reliability according to pre-defined standards for ICC and CV in both ultrasound imaging and isometric trunk and hip extensor strength testing. Inter-rater reliability, where the same rater traced the images, but different sonographers performed the ultrasound imaging, was “excellent” for the quadratus lumborum and “good” for the lumbar multifidus muscle at the fifth lumbar vertebral level and Inter-rater reliability, where the same sonographer performed the ultrasound imaging but different raters traced the images, was “good” for the lumbar multifidus muscle at the fifth lumbar vertebral level and “moderate” for the quadratus lumborum muscles.

Reliability of ultrasound imaging for assessing lumbar multifidus muscle at the fifth lumbar vertebral level muscle thickness has been assessed in previous investigations (Cuellar et al., 2017; Djordjevic et al., 2014; Mangum et al., 2016; Wallwork et al., 2007). However, to our knowledge, no studies have examined the reliability of ultrasound imaging for quadratus lumborum cross-sectional area. Furthermore, previous research evaluating the reliability of measuring the lumbar multifidus muscle at the fifth lumbar vertebral level via ultrasound imaging did not use cross-sectional area as their main outcome measure, opting for thickness measurements instead. The reliability of lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area was comparable to previous investigations (Cuellar et al., 2017; Djordjevic et al., 2014; Mangum et al., 2016; Wallwork et al., 2007) with only inter-rater reliability of the lumbar multifidus muscle at the fifth lumbar vertebral level showing an ICC < 0.9, although still considered "good" reliability. Based on the recommendation by Koo & Li (2016) using lower bounds of the ICC to interpret reliability of a measure intra-rater reliabiity of the lumbar multifiuds at the fifth lumbar vertebrae and quadratus lumborum had "good" reliability. Inter-rater reliability where the same assessor traced images by different sonographers of the quadratus lumborum measures was also "good" but the lumbar multifidus at the fifth lumbar vertebrae only had "moderate" reliability. Different assessors tracing the same image only yielded "moderate" to "poor" reliability in our sample. Following recommendations by Using the Bland-Altman method showed one outlier data point for intra- and inter-rater reliability in the lumbar multifidus muscle at the fifth lumbar vertebral level and quadratus lumborum data suggesting less than 95% of data being within the limits of agreement. The lacking agreement could be due to the small sample size of ten recreationally active healthy adults that is highly susceptible to one outlier data point and could be improved by a larger study including more participants. Regression plots additionally show acceptable (Atkinson & Nevill, 1998) intra-rater reliability for both lumbar multifidus muscle at the fifth lumbar vertebral level and quadratus lumborum while inter-rater data is below the conventional threshold with more variability shown in the quadratus lumborum measures. Both lumbar multifidus muscle at the fifth lumbar vertebral level and quadratus lumborum cross-sectional area have been used in different investigations assessing their associations with lower limb injury risk (Hajek et al., 2022; Hides et al., 2020; Hides & Stanton, 2017), therefore our demonstration of the reliability of these measures helps better understand the strengths and limitations of the basis of research conducted using these muscles' morphologies. With the average cross-sectional area of the lumbar multifidus in this sample being 7.49cm^2 and an MDC of 0.17 cm^2 any

2.2% change in cross-sectional area can be detected via ultrasound imaging and recent investigations showing a difference of up to 20% between injured and uninjured players (Hides et al., 2020) a high degree of confidence exists that clinically important changes can be measured.

The present study developed and assessed the reliability of a novel field test for evaluating isometric trunk and hip extensor strength, which is based on a modified version of the Sorensen test. This modified test was designed that was able to quantify maximum strength and strength endurance using a 65s protocol (5s MVIC, 5s rest, 45s MCIV, 5s rest, 5s MVIC). Between-session reliability was assessed with one author performing all tests. These results demonstrated "excellent" reliability for both maximum strength and strength endurance. Using the recommendation by Koo & Li (2016) both maximum strength and strength endurance had still had "good" reliability. No studies have used the isometric trunk and hip extensor strength test yet but researchers have to be aware that the MDC corresponds to a 12% change in maximum trunk and hip extensor strength and should interpret their results accordingly. Previous research investigating the reliability of the standard Sorensen test reported comparable ICC values: Latimer et al. (1999): ICC=0.83; 95% CI, 0.62–0.93; Keller et al. (2001b): ICC=0.93, CV=20%; Arab et al. (2007): ICC=0.80.

4.7.1. Limitations

All investigations come with certain limitations and unfortunately the modified Sorensen test was only performed by one assessor and the results could be strengthened by having a second rater performing the strength test. Ideally an equal sample of male and female participants would have been used but due to the convenience sample employed, a larger portion of male participants volunteered to take part in this study. While validity of ultrasound imaging for lumbar muscle morphology was previously assessed, (Hides et al., 1995) there is no data available if the presented modification of the Sorensen test is a valid tool to measure trunk and hip extensor maximum strength and strength endurance. These data were previously published for the original Sorensen test (Coorevits et al., 2008) but not yet investigated for the presented modification. The study initially planned to use the same sample of healthy active participants but Covid-19 related campus closures as well as the availability of ultrasound imaging equipment during that timeframe required a reduction of the sample size and made it impossible to compare between both cohorts.

4.7.2. *<u>Future directions</u>*

Future studies assessing the reliability of lumbar muscle morphology and strength should make sure that multiple raters are able to perform all testing sessions to give a comprehensive overview of the reliability of all utilised measures. If these measures are to be used in a cohort comprised of elite athletes, it may be beneficial to assess the reliability in such a cohort as well. Investigating the validity of the modified Sorensen test using further medical imaging and/or methods assessing muscle activation and reliability of the measures in clinical populations (e.g. low back pain) will be required to use the test in further studies. More longitudinal studies can help to assess changes of the measured parameters over time and develop normative data and future research can investigate associations between lumbar muscle morphology and isometric trunk and hip extensor strength.

4.8. Conclusion

This study was the first to assess the reliability of both ultrasound imaging analyses to measure lumbar multifidus muscle at the fifth lumbar vertebral level and quadratus lumborum cross-sectional area and a novel isometric trunk and hip extensor field test. Our findings demonstrated “excellent” reliability for the isometric trunk and hip extensor strength test and intra-rater ultrasound measurements in a cohort of healthy and recreationally active adults. Inter-rater reliability of the lumbar muscle assessment ranged from “moderate” to “excellent”. This study contributes to the growing body of literature on lumbar muscle morphology and strength assessment and provides researchers and clinicians with reliable tools for future investigations. It is important to consider further studies to validate these assessment methods in different populations, including elite athletes and clinical cohorts, and to establish normative data for these measures.

Chapter Five

Predicting Noncontact Lower Limb Injury Using Lumbar Morphology in Professional Australian Football and Rugby League Players

5.1. Publication Statement

This chapter has been peer-reviewed and accepted for publication in Medicine and Science in Sports and Exercise: **Hajek M**, Williams MD, Bourne MN, Roberts LA, Morris NR, Shield AJ, Mingin CV, Headrick J, Duhig SJ. Predicting Noncontact Lower Limb Injury Using Lumbar Morphology in Professional Australian Football and Rugby League Players. Med Sci Sports Exerc. 2022 May 1;54(5):814-820. DOI: 10.1249/MSS.0000000000002847. Epub 2021 Dec 23. PMID: 34935708.

5.1.1. Copywrite

5.1.2. Contribution

Martin Hajek's contribution included: study design, data acquisition, analysis, and reporting, interpretation of findings, and writing of the manuscript.

(Signed) [redacted] Date: 28/05/2023

Martin Hajek, PhD candidate

(Countersigned) [redacted] Date: 18/05/2023

Llion Roberts, Co-principal supervisor

5.2. Preface

Following identifying acceptable levels of reliability for the main outcome measures, data collection with several Australian professional AFL and NRL clubs was started. The data collection took place during the preseason in January and February 2020 where the research team travelled to four major cities and visited seven professional clubs' facilities. Both ultrasound and trunk and hip extensor strength data were collected during the same data collection process. This study presents results from only the ultrasound data collected during this process with the trunk and hip extensor strength data presented in chapter six.

5.3. Abstract

Introduction: Non-contact lower limb injuries are common within the AFL and NRL. Smaller (<8.5 cm^2) lumbar multifidus at the fifth vertebral level and larger (>8.2 cm^2) quadratus lumborum cross-sectional area have been associated with increased non-contact lower limb injury risk in AFL players. These associations have not been explored in an NRL cohort. This study attempted to replicate previous research findings by confirming that muscle morphology is associated with non-contact lower limb injury. **Methods:** AFL (n=87) and NRL (n=151) players underwent lumbar multifidus from second to fifth lumbar vertebral level and quadratus lumborum cross-sectional area ultrasound measures during preseason. Each club's medical staff reported all non-contact lower limb injuries sustained in the subsequent regular season. lumbar multifidus and quadratus lumborum cross-sectional area, age, body mass index and non-contact lower limb injuries were analysed using multivariable logistic regression. **Results:** Seventy-two players sustained a non-contact lower limb injury in the 2020 regular season (AFL=21, NRL=51). The multivariable logistic regression (OR: 1.36, 95%CI: 1.02-1.85, p=0.038) identified AFL players with larger quadratus lumborum cross-sectional area at increased risk of sustaining a non-contact lower limb injury during the regular season but no relationship was found for lumbar multifidus cross-sectional area and non-contact lower limb injuries in the AFL (OR: 1.01, 95%CI: 0.36-2.78, p=0.591) or NRL (OR: 0.63, 95%CI: 0.29-1.33, p=0.149). **Conclusions:** AFL players who sustained regular season non-contact lower limb injuries had larger quadratus lumborum cross-sectional areas in pre-season tests. no significant associations between either lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area or lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio and regular season non-contact lower limb injuries were found.

Key Words: Ultrasound; Lumbar multifidus, Australian Rules Football, Rugby League, Lower limb injury

5.4. Introduction

The AFL and NRL are elite national competitions for Australian rules football and rugby league, respectively. While both are full contact sports, the physical demands differ significantly (Colby et al., 2014; Johnston et al., 2014). AFL matches have a higher emphasis on jumping, landing, picking up and kicking the ball and high-speed running while head-on collisions are more prevalent in the NRL (Pyne et al., 2005). Nevertheless, lower limb injuries such as hamstring strains (~25 missed matches per club per regular season in AFL, ~21 missed matches per club per regular season in NRL) and ACL injuries (~16 missed matches per club per regular season in AFL, ~12 missed matches per club per regular season in NRL) result in the highest number of matches missed per club per regular season (Australian-Football-League, 2018; O'Connor, 2019; Orchard, Seward, et al., 2013). While these football codes differ in terms of rules and gameplay, they share similar rates and mechanisms of non-contact lower limb injuries. Further, the high incidence and prevalence of such injuries warrants investigation into the somewhat futile attempts to reduce these rates despite widespread attention in recent years.

Trunk muscle morphology has been identified as a risk factor for lower limb injury in Australian rules football. Hides and colleagues conducted a series of studies (Hides et al., 2020; Hides et al., 2011; Hides & Stanton, 2017; Hides et al., 2014) on AFL players, identifying a smaller (< 8.5 cm^2) cross-sectional area of the lumbar multifidus at the fifth vertebrae, a larger (> 8.2 cm^2) cross-sectional area of the quadratus lumborum, and muscle size imbalance (quadratus lumborum > lumbar multifidus muscle at the fifth lumbar vertebral level) as modifiable risk factors for non-contact lower limb injuries. Although hypothetical, the role of the lumbar muscles in trunk stability (Panjabi et al., 1989) and stiffness are proposed as the most likely explanation for their relationship with non-contact lower limb injuries (Zazulak et al., 2008). Being able to quickly control the trunk during unanticipated external perturbations can mitigate the risk of sustaining an ACL injury (Song et al., 2022; Zazulak et al., 2008). These findings have influenced sports physiotherapy practice and led to other sport-specific research assessing the lumbar morphology (Roy et al., 2021; Schryver et al., 2020), despite no large-scale prospective studies being conducted in other sports to date.

According to Bahr (2016) the predictive capacity of identified injury risk factors is limited, and a three-step approach is required to assess validity, including (1) identification of risk factors, and (2) validating previously defined risk factors and cut-off points in separate cohorts. Should the previous two steps identify a potential risk factor, a randomised control trial should be employed to assess the effectiveness of screening and exercise interventions. Using Bahr's (2016) approach, whilst dichotomised cut-offs for lumbar multifidus muscle at the fifth lumbar vertebral level have been reported, replication of risk factors in an independent cohort is yet to be undertaken. Before the implementation of a randomised controlled trial using techniques targeting the reduction of non-contact lower limb injuries, investigations in separate cohorts are warranted.

Therefore, the aim of this study is to replicate the predictive model outlined by Hides and colleagues (Hides & Stanton, 2017) in the AFL cohort. Secondly, the study aims to explore if lumbar morphology has predictive capabilities in a separate cohort (NRL).

5.5. Methods

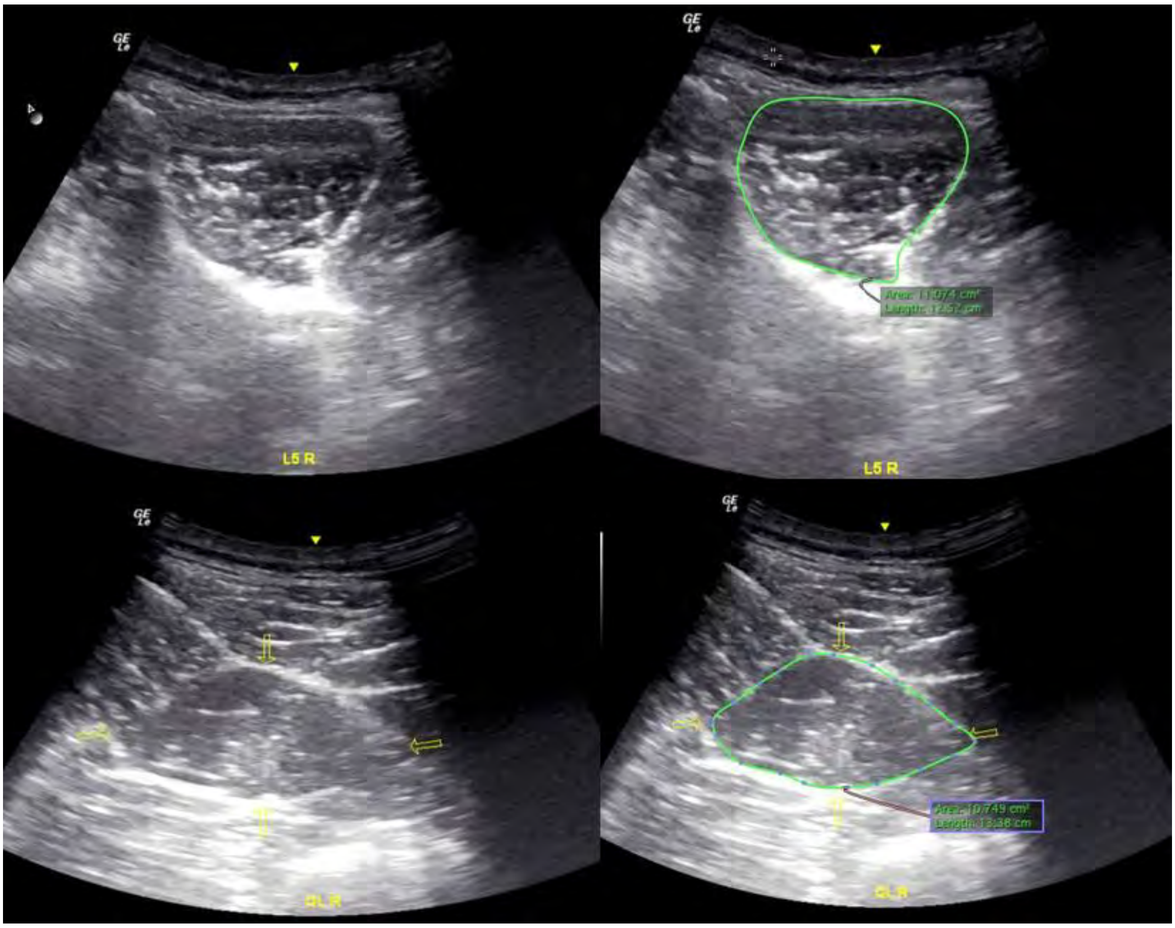
5.5.1. Study Design

This prospective cohort study recruited professional male football players (n=238) from two AFL (n=87) and four NRL (n=151) clubs. All players provided written, informed consent before volunteering to participate in this study, which was approved by the Griffith University Human Ethics Review Board (GU Ref No: 2019/106). Each player had their lumbar multifidus and quadratus lumborum cross-sectional area measured using 2D ultrasound imaging at a single timepoint in preseason (January and February 2020). Demographic information and injury history details were provided by the club's medical staff. Two assessors (MH and CM) collected ultrasound imaging data during a regular strength training session in accordance with the present support staff. All currently uninjured players in the club's senior squad were asked to participate in the ultrasound imaging assessment. Details of all non-contact lower limb injuries sustained in the subsequent regular season were reported to the researchers by club's medical team.

5.5.2. Ultrasound Assessment

lumbar multifidus images were obtained using *B*-mode ultrasound (LOGiQ-e, GE Healthcare, Milwaukee, WI) with a 5-MHz curvilinear transducer. All imaging acquisition parameters were kept consistent (frequency: 5MHz, gain: 60, depth: 8.0cm). Ultrasound reliability and validity of lumbar multifidus measurements have previously been confirmed (Wallwork et al., 2007). All ultrasound measurements were obtained by two sonographers (MH, CM) who had high intra- and inter-rater reliability (Intra-rater ICC: 0.94; inter-rater ICC: 0.89). A separate unpublished reliability study was conducted (n=10) on two separate occasions, one week apart with both sonographers independently taking scans using the same device and settings. Tracing of the lumbar multifidus and quadratus lumborum cross-sectional area were performed by the same assessor (MH) with high intra-rater reliability (ICC: 0.98). All ultrasound measures were collected with players laying prone on a plinth after five minutes of rest. The spinous processes of lumbar (L)2, L3, L4 and L5 were palpated and marked with a black pen, and positions of the markings confirmed using ultrasound and corrected if necessary. The transducer was oriented in the transverse plane at each vertebra to measure lumbar multifidus cross-sectional area (Hides et al., 1995). Quadratus lumborum cross-sectional area was measured at L3-L4 where it has the largest cross-sectional area (Narici, 1999). Images were analysed off-line using OsiriX software (Lite-version, Pixmeo SARL, Geneva, Switzerland). Outer borders of the muscles were traced manually (Figure 16), and cross-sectional area calculated.

Figure 16: Exemplar ultrasound imaging measurements of lumbar multifidus at fifth lumbar vertebral level and quadratus lumborum assessment. Top images show the lumbar multifidus at fifth lumbar vertebral level before and after tracing of cross-sectional area, and bottom images depict the quadratus lumborum.



5.5.3. <u>*Prospective Injury Definition*</u>

The primary outcome of this study was the occurrence of non-contact lower limb injuries during the 2020 regular season. Non-contact lower limb injuries were diagnosed by each club's medical staff and defined as physical conditions related to playing in the NRL or AFL resulting in a player missing at least one game (Orchard et al., 2010). Injury data from the 2020 regular season was provided by each club's physiotherapist as a standardised report which is provided to each competition's governing body (AFL or NRL). Injuries were coded in the Orchard Sports Injury Classification System (OSICS) and included information about injury occurrence and mechanism (i.e., running, jumping, landing, change of direction, direct collision) (Orchard et al., 2010).

5.5.4. Statistical Analyses

Statistical analysis was performed using JMP (V.15.2.0 Pro, Statistical Discovery Software SAS Inc., Cary, North Carolina, USA). Where appropriate, data were tested for normal distribution and homoscedasticity using Shapiro-Wilks and Levene's tests. Means and standard deviations for age, height, weight, BMI, and lumbar morphology were reported. Two-tailed t-tests were used to compare age, height, weight, BMI and lumbar muscle cross-sectional area between AFL and NRL cohorts. The study used a convenience sample based on professional clubs willing to participate. Effect sizes were calculated using Cohen's D and interpreted as follows: <0.2 trivial, 0.2-0.49 small, 0.5-0.8 medium, >0.8 large (Berben et al., 2012).

Pearson's correlation was used to determine the relationship between the left and right side of lumbar multifidus and quadratus lumborum cross-sectional area. When analysing all non-contact lower limb injuries players were split into groups based on football code (AFL or NRL).

Independence of the continuous variables (lumbar multifidus cross-sectional area at all levels, quadratus lumborum cross-sectional area, age, height, weight) was assessed by Pearson's correlation coefficient with and coefficient >0.7 being interpreted as strong and excluded from the multivariable assessment. Risk factor cut-offs defined by Hides and Stanton (2017) were incorporated as follows: 1) lumbar multifidus muscle at the fifth lumbar vertebral level < 8.5 cm^2, 2) quadratus lumborum > 8.2 cm^2, 3) lumbar multifidus muscle at the fifth lumbar vertebral level /quadratus lumborum < 1 and data was dichotomised accordingly. Odds ratios (unadjusted and adjusted for age, height and weight) were calculated using a multivariable logistic regression model with age, height and weight as covariates (Table 5). The models were evaluated according to receiver-operator characteristics (ROC), area under the curve (AUC) and a confusion matrix. AUC was interpreted as: 0.5-0.7 no discrimination, 0.7-0.8 acceptable, 0.8-0.9 excellent 0.9-1.0 outstanding (Hosmer et al., 2000). Null and alternative hypothesis were tested using Fisher's exact test, and a $\chi 2$ test was used to calculate p-values of the likelihood ratio. For all analyses, alpha was accepted as $p<0.05$.

Table 5: Variables used to determine OR and build logistic regression models.

Odds ratios	Univariable logistic regression	Multivariable logistic regression
LM L5 CSA (cm^2)	LM L5 CSA (cm^2)	LM L5 CSA (cm^2) and QL CSA (cm2)
QL CSA (cm^2)	QL CSA (cm^2)	LM L5 CSA (cm^2) and QL CSA (cm2) and age and BMI
LM L5/QL	LM L5/QL	LM L5 CSA (cm^2) and QL CSA (cm2) and LM L5/QL and age and BMI

Age (years)

BMI

LM L5 = Lumbar multifidus level L5, QL = Quadratus lumborum, BMI = body mass index, CSA = Cross sectional area

5.6. Results

During the 2020 pre-season, 238 professional football players were assessed with a complete follow up obtained for all players (Table 6). A total of 72 (30%) players sustained a non-contact lower limb injury. The most common injuries observed were hamstring strains (n=28), knee ligament injuries (n=21), calf muscle and Achilles tendon injuries (n=14) and hip/groin injuries (n=10).

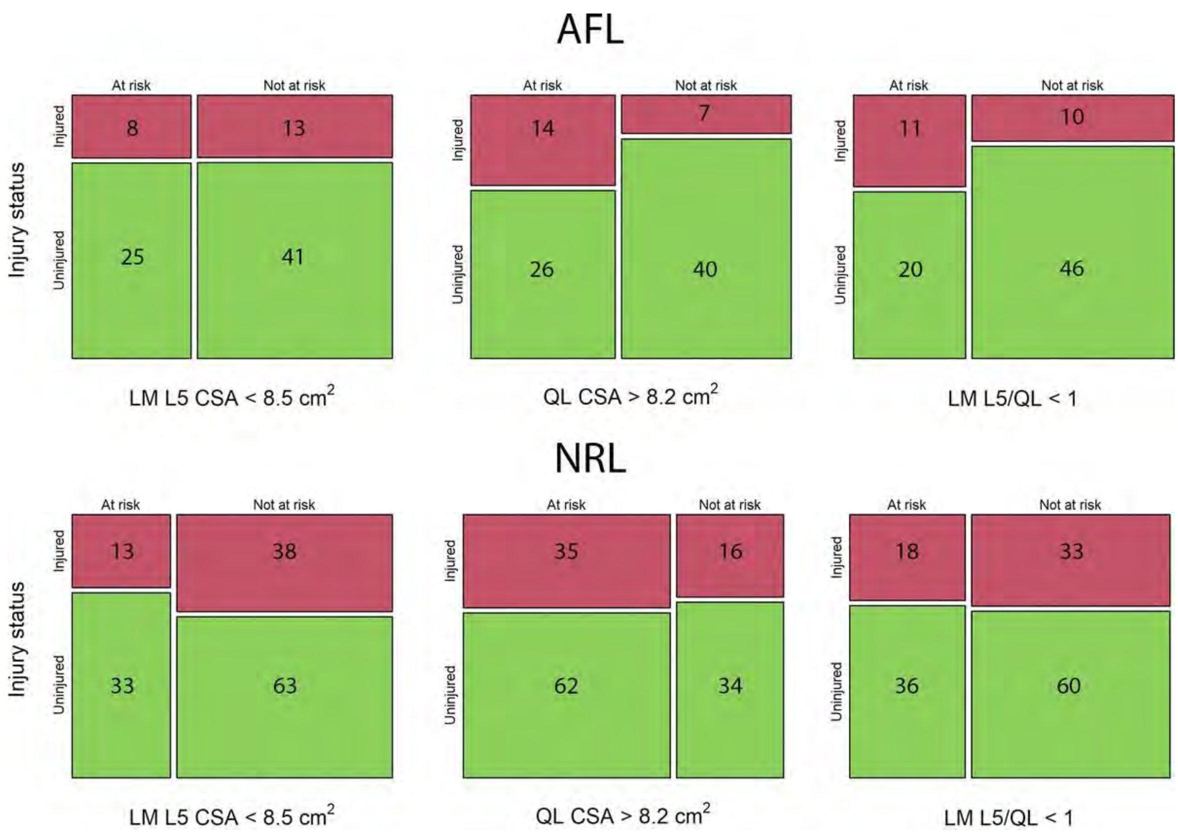
Table 6: Player demographics by football code

	AFL		NRL			
	Mean	SD	Mean	SD	p-value	Effect size
n	87		151			
Age (years)	23.8	3.9	24	3.8	0.713	-0.05
Height (cm)	188.1	7.7	186.2	6	0.0328*	0.28
Weight (kg)	86.9	8.7	100	10.2	<0.0001*	-1.38
BMI (kg/m^2)	24.5	1.32	28.8	2.29	<0.0001*	-2.29
L2 (cm^2)	3.71	0.77	4.01	0.86	0.009*	-0.36
Asymmetry	0.152	0.126	0.155	0.149	0.873	-0.02
L3 (cm^2)	4.75	1.02	5.09	1.07	0.016	-0.33
Asymmetry	0.162	0.172	0.22	0.46	0.259	-0.16
L4 (cm^2)	6.92	1.61	6.9	1.63	0.956	0.01
Asymmetry	0.358	0.441	0.266	0.295	0.056	0.24
L5 (cm^2)	8.74	1.46	9.41	1.77	0.003*	-0.42
Asymmetry	0.454	0.497	0.324	0.365	0.0222*	0.29
QL (cm^2)	8.18	1.81	8.84	2.33	0.023*	-0.32
Asymmetry	0.691	0.88	0.718	0.815	0.81	-0.03

AFL=Australian Football League, NRL=National Rugby League, L=Lumbar, QL=Quadratus lumborum, * represents statistical significance

Measurements of lumbar morphology showed high correlation between the left and right side on all lumbar levels (lumbar multifidus second lumbar vertebral level=0.96, lumbar multifidus third lumbar vertebral level=0.92, lumbar multifidus fourth lumbar vertebral level=0.95, lumbar multifidus muscle at the fifth lumbar vertebral level =0.94, quadratus lumborum=0.87) with no significant correlation between continuous variables (Table 7). Following dichotomisation of the lumbar muscles, 81 (at risk = 34%) players (33 (at risk = 37%) AFL, 48 (at risk = 32%) NRL) were classified as having a lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area < 8.5 cm^2, 138 (at risk = 57%) players (40 (at risk = 45%) AFL, 98 (at risk = 67%) NRL) had a quadratus lumborum cross-sectional area > 8.2 cm^2, and 86 (at risk = 36%) players (31 (at risk = 35%) AFL, 55 (at risk = 37%) NRL) had a lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio < 1.. Using a dichotomised approach shows AFL players with a quadratus lumborum cross-sectional area > 8.2 cm^2 had significantly increased risk (OR=3.08, 95%CI=1.09-8.64, p=0.026) of sustaining a non-contact lower limb injury. No increased risk was observed for players below the lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area (OR=1.01, 95%CI=0.36-2.78, p=0.591) or lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio (OR=2.53, 95%CI=0.93-6.91, p=0.059) cut-offs in either cohort (Figure 17). None of the previously defined cut-offs displayed a significant increase in non-contact lower limb injury risk in the NRL group (lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area: OR=0.63, 95%CI=0.29-1.33, p=0.149; quadratus lumborum cross-sectional area OR=1.22, 95%CI=0.59-2.50, p=0.366; lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio: OR=0.91, 95%CI=0.44-1.84, p=0.468).

Figure 17: Mosaic plots for LM L5, QL, and LM to QL ratio cut-off parameters.



Abbreviations: AFL=Australian Football League, NRL=National Rugby League, LM L5= lumbar multifidus muscle at the fifth lumbar vertebral level, QL=quadratus lumborum, CSA=cross-sectional area

Table 7: Adjusted and unadjusted OR for LM L5 CSA, QL CSA and LM L5 to QL ratio. In case of adjusted model age, height and weight are used as covariates.

	AFL								
	Unadjusted			Adjusted			LM to QL Ratio		
	OR	95%CI	p	OR	95%CI	p	OR	95%CI	p
LM	0.89	0.61-1.27	0.523	0.90	0.62-1.30	0.591	1.54	0.50-6.08	0.489
QL	1.33	1.01-1.79	0.049*	1.36	1.02-1.85	0.712	0.80	0.21-2.42	0.712
LM/QL							0.01	0.00-74.11	0.375
	NRL								
	Unadjusted			Adjusted			LM to QL Ratio		
	OR	95%CI	p	OR	95%CI	p	OR	95%CI	p
LM	1.00	0.82-1.22	0.991	1.01	0.82-1.24	0.913	1.27	0.87-2.01	0.260
QL	1.06	0.91-1.23	0.477	1.06	0.91-1.25	0.437	0.81	0.48-1.22	0.356
LM/QL							0.13	0.00-2.05	0.224

Abbreviations: AFL=Australian Football League, NRL=National Rugby League, OR= odds ratio, 95%CI = 95% confidence interval, LM=lumbar multifidus, QL=quadratus lumborum, L5=fifth lumbar vertebrae, LM/QL = LM L5 to QL ratio

For AFL players, both unadjusted and adjusted regression models identified increased quadratus lumborum cross-sectional area (Unadjusted: OR=1.33, AUC=0.66; adjusted: OR=1.36, AUC=0.68) as a risk factor for sustaining regular season non-contact lower limb injuries (Table 7). Neither cross-sectional area of the lumbar multifidus muscle at the fifth lumbar vertebral level or lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio were related to regular season non-contact lower limb injury risk in AFL players. The regression model did not identify any of the measured parameters to be significantly associated with lower limb injury risk in the NRL cohort. Sensitivity, specificity, and AUC details can be found in table 8. Only the model including lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio can be considered acceptable (AUC: 0.7-0.8) under established principles.

Table 8: Receiver operator characteristics of adjusted and unadjusted regression models.

	AFL		
	Unadjusted	Adjusted	LM/QL
Sensitivity	0.86	0.81	0.67
Specificity	0.5	0.55	0.71
AUC	0.66	0.68	0.7
	NRL		
	Unadjusted	Adjusted	LM/QL
Sensitivity	0.86	0.49	0.71
Specificity	0.24	0.57	0.52
AUC	0.52	0.47	0.58

AFL=Australian Football League, NRL=National Rugby League, AUC = Area under the curve, LM/QL= lumbar multifidus to quadratus lumborum ratio

5.7. Discussion

The presented study aimed to replicate the predictive model for non-contact lower limb injuries in AFL players based on lumbar morphology measures described by Hides (Hides & Stanton, 2017) and to explore whether similar associations existed in an NRL cohort. Our results show limited capacity of lumbar morphology to assess lower limb injury risk in the AFL cohort and no association with non-contact lower limb injuries in the NRL cohort. While increased quadratus lumborum cross-sectional area was replicated as a risk factor for non-contact lower limb injury in the AFL population, this association was not found for lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area nor the affiliated lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio. These data may suggest football code specific injury risk factors.

Lumbar muscle morphology is a commonly cited risk factor for non-contact lower limb injury in football (Hides et al., 2020; Hides et al., 2011; Hides & Stanton, 2017; Hides et al., 2014). Previous investigations report increased risk of sustaining a non-contact lower limb injury, in either the pre- or regular season, for both dichotomised and continuous cross-sectional area measurements of the lumbar multifidus muscle at the fifth lumbar vertebral level and quadratus lumborum muscles as well as the ratio between both in AFL players (Hides et al., 2020). Interestingly, our data suggest only increased quadratus lumborum cross-sectional area and was related to non-contact lower limb injuries during the regular season for AFL players. In contrast with previous investigations (Hides & Stanton, 2017), no significant associations between either lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area or lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio and regular season non-contact lower limb injuries were found. While Hides and colleagues have recently (Hides et al., 2020) reported similar relationships between trunk morphology and non-contact lower limb injury our study was unable to fully replicate these findings. A recent study performed on university level rugby players (Levesque et al., 2020) found associations between increased multifidus asymmetry and non-contact lower limb injury risk and reduced thickness change during submaximal contractions in standing position with non-contact lower limb injuries which was not included in the aims of this study but warrants further investigation. Discrepancies leading to the lack of agreement between studies may be explained by possible interclub differences in training practices. Future research should explore the effect of different exercise and individual coordination strategies on trunk muscle activation patterns.

We would like to highlight that expanding the approach to assess non-contact lower limb injury risk using lumbar morphology measures in a different football code (NRL) did not show transferability to a sport that has similar rates and mechanisms of non-contact lower limb injuries (Cochrane et al., 2007; Saw et al., 2018). It is outside the scope of this study to provide explanations as to the mechanism which relates quadratus lumborum as a risk factor in one football code but not the other. However, the unobserved relationship between trunk morphology and non-contact lower limb injury in NRL players might be related to NRL players having a significantly larger quadratus lumborum and lumbar multifidus muscle at the fifth lumbar vertebral level than AFL players leading to a larger percentage of the cohort being above the pre-defined cut-off for quadratus lumborum cross-sectional area ($> 8.2\ cm^2$) and lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area ($< 8.5\ cm^2$). This might cause a difference in the dichotomous injury risk assessment but does not influence the logistic regression model only partly explaining the lack of relationship between lumbar morphology and non-contact lower limb injury risk in NRL. Further, while these non-contact injuries share the same mechanisms (i.e., running, cutting, decelerating) the demands of each football codes differ, such as a larger percentage of sprinting efforts being observed in the NRL and more jumping, landing, picking up and kicking the ball required in the AFL (Colby et al., 2014; Johnston et al., 2014). AFL players are significantly taller but lighter than their NRL counterparts and these differences in body composition and muscle structure could potentially highlight why measures of lumbar morphology has no predictive capacity for NRL players.

It has been proposed that the link between lumbar multifidus and quadratus lumborum morphology and non-contact lower limb injury risk is related to these muscles' role in spinal stabilisation. The most common assumption is based on the lumbar multifidus being responsible for lumbar spine stability during locomotion (Bogduk et al., 1992a; Macintosh & Bogduk, 1986; Maughan et al., 1983) and its high density of muscle spindles (Nitz & Peck, 1986a). While the function and biomechanics of the lumbar multifidus are well explained (Bogduk et al., 1992a; Macintosh & Bogduk, 1986 Macintosh et al., 1986; Panjabi, 1992) there is still uncertainty about the exact function of the quadratus lumborum (Phillips et al., 2008). Spinal stability, especially in the dynamic setting of competitive sports is difficult to define (Reeves et al., 2007) and requires accurate neuromuscular feedback in conjunction with sufficient muscular strength (Zazulak et al., 2008). The lumbar multifidus is theorised to provide the neuromuscular feedback (Nitz & Peck, 1986a) and to quickly reposition the spine via reflex control (Brumagne et al., 2000). It has been hypothesised that high quadratus lumborum activation levels may be associated with trunk stiffness (Freddolini et al., 2014) which leads to a greater risk of injury (Franklin et al., 2003; Milner, 2002). Increased quadratus lumborum muscle activation (Park et al., 2013) and trunk stiffness (Lee et al., 2006) were observed in patients suffering from chronic lower back pain, potentially to compensate for impaired muscle spindles in the lumbar multifidus.

Based on the observed increased quadratus lumborum cross-sectional area in patients with lower back pain, it has been suggested that greater quadratus lumborum cross-sectional areas are associated with longer durations of muscle work to compensate for an underactive lumbar multifidus when providing trunk stability (Schuermans, Danneels, et al., 2017). This concept was used to support the finding of an increasing quadratus lumborum cross-sectional area and decreasing lumbar multifidus cross-sectional area over the AFL regular season (Zazulak et al., 2008; Zazulak et al., 2007a, 2007b). Schuermans and colleagues (Schuermans, Danneels, et al., 2017) suggest a relationship between decreased trunk muscle activity (thoracic and lumbar erector spinae) and hamstring injuries in male soccer players. It should be noted that no stability measures were taken, and currently, the only relationship between presumed indices of spinal instability and ACL injuries has been observed in female athletes (Zazulak et al., 2008; Zazulak et al., 2007a, 2007b). Recent research (van den Hoorn et al., 2020) casts doubt to whether trunk stiffness increases with acute lower back pain. Furthermore, no evidence is currently available to suggest that the maladaptation found in patients suffering from lower back pain also occurs in AFL players over the course of a regular season. This warrants further investigations into trunk stiffness changes as an effect of high intensity exercise. Measures of lumbar muscle strength can also be incorporated in future studies given adequate strength is required for proper reflex control (Zazulak et al., 2008).

We recognise that our reported AUC of 0.7 is deemed acceptable (Hosmer et al., 2000) however it should be recognised that this remains closer to random discrimination (0.5) than perfect prediction (1). Therefore, while the presented model can identify a general risk factor on a population level it is not applicable to predict injuries on an idividual basis. The authors acknoledge that this limits the capacity of the quadratus lumborum cross-sectional area as a predictor for iregular season non-contact lower limb injuries.

The present study is not without limitations. This study was conducted during the 2020 seasons with clubs affected by COVID-19 restrictions, which increased confounding variables. There was a 12-week break between round-1 and -2 in the AFL season and a 10-week break between round-2 and -3 in the NRL season leading to a period away from the club's facilities between pre-season and regular season, potentially leading to inconsistent training loads for players. The AFL reduced the number of matches played from 22 to 17 and the playing time per quarter from 20 to 16 minutes resulting in reduced training and match exposure. The NRL extended its regular season beyond the usual conclusion date while keeping the same number of matches played. Finally, the current analysis replicated a previously reported model that used injury data from the 2015 AFL playing season and the authors acknowledge that rule changes to the game have changed gameplay and likely training practices which would affect injury risk factors.

Our findings suggest a relationship between non-contact lower limb injuries and quadratus lumborum cross-sectional area is present and specific to AFL, but not generalised to NRL players. This study is unable to reproduce some of the predictive variables reported by Hides and colleagues (Hides & Stanton, 2017) with no relationship between non-contact lower limb injury risk and reduced lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area and reduced lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio identified.

5.8. Acknowledgments

This study was funded by an internal Griffith University New Researcher Grant awarded to SD, MB and JH in 2019.

The authors would like to thank the teams (Canberra Raiders, Manly Warringah Sea Eagles, Melbourne Football Club, Melbourne Storm, Port Adelaide Football Club, Sydney West Tigers) and all players who kindly participated in the study.

5.9. Conflict of Interest

The authors declare that there are no conflicts of interest. There exist no professional relationships with companies or manufacturers who will benefit from the results of this study. The results of the present study do not constitute endorsement by ACSM. The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

Chapter Six

Associations Between Hamstring Strain and Knee Ligament Injuries with Isometric Trunk and Hip Strength and Morphology in Professional Australian Rules Football and Rugby League Players

6.1. Publication Statement

This chapter has been submitted and is under review for publication

Hajek, M., Williams, M. D., Bourne, M. N., Roberts L. R., Morris, N. R., Shield, A. J., Headrick, J., Duhig, S. J. (2023). Associations between hamstring strain and knee ligament injuries with isometric trunk and hip strength and morphology in professional Australian rules football and rugby league players. *Unpublished*

6.1.1. Contribution

Martin Hajek's contribution included: study design, data acquisition, analysis, and reporting, interpretation of findings, and writing of the manuscript.

(Signed) [redacted] Date: 28/05/2023

Martin Hajek, PhD candidate

(Countersigned) [redacted] Date: 28/05/2023

Llion Roberts, Co-principal supervisor

6.2. Preface

The trunk and hip extensor strength data collected in the same data collection as in chapter five is presented in this study. In the previous chapter a significant association between quadratus lumborum cross-sectional area and non-contact lower limb injury risk was found in AFL players only. Combining measures of lumbar muscle morphology with a measure of trunk and hip extensor maximum strength and strength endurance may improve the estimation of non-contact lower limb injury risk. A subgroup analysis for the two most prevalent types of non-contact lower limb injuries was performed to further refine the estimation of injury risk.

6.3. Abstract

Objectives: Lumbar multifidus and quadratus lumborum cross sectional area potentially increase lower limb injury risk. Including functional measures with structural may improve risk models. Relationships between isometric trunk and hip strength and morphology were explored with hamstring and knee ligament injury risk in AFL and NRL players.

Design: Prospective cohort study

Methods: During the AFL and NRL 2020 preseasons, isometric strength (n=153, 5s (maximum strength) and 45s (strength-endurance), and morphology (n=238, lumbar multifidus muscle at the fifth lumbar vertebral level and quadratus lumborum cross-sectional area) were assessed. Logistic regression and decision trees were used to explore associations between maximum strength, strength endurance, lumbar multifidus muscle at the fifth lumbar vertebral level and quadratus lumborum cross-sectional area, age, previous injury, and hamstring and knee ligament injuries.

Results: Nineteen hamstring and 13 knee ligament injuries occurred. Greater strength endurance (OR: 0.42, 95%CI: 0.23-0.74, p: 0.004) and maximum strength (OR: 0.55, 95%CI: 0.31-0.94, p: 0.039) reduced hamstring injury risk. Knee ligament injury risk increased with larger lumbar multifidus muscle at the fifth lumbar vertebral level (OR=1.66, 95%CI=1.14-2.45) and lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio (OR=1.57, 95%CI=1.13-2.23). Decision tree models suggested low strength endurance (<99Nm) was characteristic of hamstring strains yet those with high ($\geq$1.33) lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio were protected. Knee ligament injuries were classified by larger ($\geq$8.49cm^2) lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area, greater ($\geq$1.25) lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio, and lower maximum strength (<9.24 N/kg).

Conclusions: Hamstring injury risk increased in players with lower maximum strength and strength-endurance. Knee ligament injury risk greater in players with larger lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area and lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio and lower maximum strength.

Keywords: Back muscles; Football; Ligaments, Articular; Strain Injury

6.4. Introduction

Australian rules football and rugby league are both full contact sports performed at the elite level in Australia. Despite different physical demands of both sports (Colby et al., 2014; Johnston et al., 2014) the incidence of non-contact lower limb injuries are similar (AFL, 2020; McCaskie et al., 2021; O'Connor, 2019; Orchard et al., 2010) with hamstring strains and knee ligament injuries most prevalent (Australian-Football-League, 2018; Orchard, Seward, et al., 2013). Hamstring strains and knee ligament injuries presumably result from complex and potentially non-linear interactions between several modifiable and non-modifiable risk factors (Collings et al., 2021; Green et al., 2020; Green & Pizzari, 2017; Hajek et al., 2022; Smith et al., 2012a, 2012b), which may be specific to the demands of individual sports. Risk factor identification is an important step in developing strategies targeted at reducing non-contact injuries (Finch, 2006; van Mechelen et al., 1992) and older age and previous injury are the two most consistently identified non-modifiable risk factors for hamstring strain and knee ligament injuries (Collings et al., 2021; Green et al., 2020; Green & Pizzari, 2017; Smith et al., 2012a, 2012b; Webster & Hewett, 2018; Whittaker et al., 2015). Hamstring strength and strength-endurance (Green et al., 2020; Myer et al., 2009), hip abduction and external rotation strength, hip kinematics during running (Schuermans, Van Tiggelen, et al., 2017) and trunk proprioception (Zazulak et al., 2007a) were all associated with greater propensity for hamstring strain or knee ligament injury.

Australian rules football players with smaller cross-sectional area of the lumbar multifidus at the fifth lumbar vertebral level and larger quadratus lumborum cross-sectional area have been shown to have an increased risk of any subsequent non-contact lower limb injuries (Hides et al., 2020; Hides et al., 2011; Hides & Stanton, 2017; Hides et al., 2014). Reduced contractile ability of the lumbar multifidus muscle at the fifth lumbar vertebral level (Roy et al., 2021) and dominant, non-dominant side lumbar multifidus muscle at the fifth lumbar vertebral level asymmetry (Olivier et al., 2017) were also suggested to be risk factors. Recently, we replicated these studies in both AFL and NRL players (Hajek et al., 2022) finding AFL players who sustained non-contact lower limb injuries did indeed have larger quadratus lumborum cross-sectional area in preseason tests. However, trunk morphology measures of lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area or lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio offered little insight to in-season non-contact lower limb injuries in either cohort.

The lumbar multifidus and quadratus lumborum are both involved in trunk extension, rotation, and proprioception and therefore believed to influence hip and trunk kinematics during exercise, however, there is limited evidence showing a mechanistic link between lumbar muscle cross-sectional area and pooled non-contact lower limb injuries. While measures of lumbar morphology in isolation provide insight into muscle size, they fail to address force generating capacity (i.e., strength) thus considered a reductionist approach (Ruddy et al., 2019). Reducing estimation of injury risk to a select number of variables or considering variables in isolation as well as using conventional statistics that do not consider non-linear interactions can limit the applicability of the results (Ruddy et al., 2019). A multivariable approach aided by artificial intelligence methods can perform more complex injury risk assessments in team sports (Claudino et al., 2019) and the addition of muscle function tests may reveal a more informed model of combined structure (morphology) and function (strength). To address this absence of force generating capacity we developed a novel isometric trunk and hip extensor strength field-test. Based on a modification of the Sorensen test (Biering-Sorensen, 1984) to provide a measure of both maximum strength and strength endurance.

The primary aim of this study was to determine the association of preseason measures of isometric trunk and hip extensor strength and subsequent non-contact hamstring strain and knee ligament injuries in AFL and NRL players. The secondary aim was to determine whether combining trunk and hip extensor strength with lumbar morphology measures improves the injury risk model. We hypothesised that low isometric trunk and hip extensor strength and small lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area would be associated with a greater risk of subsequent non-contact hamstring strain and knee ligament injury.

6.5. Methods

6.5.1. *Study Design*

This study is a continuation of our previously published work (Hajek et al., 2022). Professional players from two AFL and four NRL clubs were recruited. All players provided written informed consent prior to participating, which was approved by the Griffith University Human Ethics Committee (GU Ref No: 2019/106). During January and February of the 2020 preseasons, 238 players (87 AFL, 151 NRL) underwent two-dimensional (2D) ultrasound imaging of their lumbar back muscles and 153 players (64%, 69 AFL, 84 NRL) also agreed to participate in a novel assessment of isometric trunk and hip extensor strength using a modified Biering-Sorensen test (Biering-Sorensen, 1984). Players were excluded from isometric trunk and hip extensor strength testing if they had a current or recent (up to three months prior) back or lower extremity injury at the time of testing in accordance with the club's medical staff. Assessments took approximately 15 minutes and were integrated into their regular schedule during a strength training session ensuring players had appropriate warm-up. Demographic, anthropometric and 12-month injury history details were collected, and team medical staff reported all non-contact lower limb injuries sustained in the 2020 competitive season.

6.5.2. *Isometric Trunk and Hip Extensor Strength Test*

Players were asked to perform a modified version of the Biering-Sorensen test (Biering-Sorensen, 1984) where they lay prone with the lower body (gluteus maximus, popliteal fold and malleoli) strapped to a plinth and upper body (superior to the iliac crest) hanging over the edge. Participants attempted to extend their hips and trunk while wearing a custom-made harness that was anchored to the floor at the level of the xyphoid process (Figure 18), thus ensuring an isometric contraction. A load cell (Vald Performance, Brisbane, Australia; sampling frequency: 400Hz) was fixed between the strap and immovable object to allow for the measurement of the trunk and hip extension force. The player's trunk was held neutral and horizontal (verified by investigators SD, MH) using a spirit level that was in contact with L5/S1 and C7. Players performed two sub-maximal warm-up repetitions followed by two MVIC using the protocol of: 5s MVIC, 5s rest, followed by a 45s MVIC (Corin et al., 2005). Our testing has shown high test-retest reliability for both 5s peak MVIC (ICC=0.89, CV=6.8%) and 45s mean MVIC (ICC=0.87, CV=8.6%) during this modified strength test (unpublished, 20 participants, seven days between measurements, age: 26±3.3 years). Isometric trunk and hip extensor force data was extracted as a comma separated value (csv) file from the software (Valdhub) and smoothed using a minimum-order 6Hz lowpass filter with a stopband attenuation of 60 dB and compensation for filter delay in Matlab (The MathWorks, Natick, Massachusetts, USA). Force produced by each participant was normalised based on body weight expressed as N/kg with maximum force produced during the 5s MVIC (maximum strength) and mean force produced during the 45s MVIC (strength endurance) used as the independent variables in the statistical analysis.

Figure 18: Illustration of the novel trunk and hip extensor strength test

6.5.3. Ultrasound Assessment

Ultrasound imaging data used in this investigation comes from the same dataset reported in our previously published study (Hajek et al., 2022) presented in chapter five in this thesis.

6.5.4. Prospective Injury Definition

The primary outcome of this study was non-contact hamstring and knee ligament injuries during the 2020 competitive AFL and NRL home and away seasons. Hamstring strain injuries were defined as acute injuries causing pain in posterior thigh regions leading to missing at least one game and the club's physiotherapy department later confirmed damage to the hamstring muscle and/or tendon (Duhig et al., 2016). Knee ligament injuries include acute injuries to the ACL, PCL, LCL and MCL sustained in relation to playing or training in the AFL and NRL and resulting in a player missing at least one game. Injury data from the 2020 playing season was provided by each club's physiotherapist as a standardised report which is provided to each competition's governing body (AFL and NRL). Injuries were coded according to the Orchard Sports Injury Classification System (OSICS) and included information about injury diagnosis, occurrence, and mechanism (Orchard et al., 2010).

6.5.5. Statistical Analysis

Statistical analysis software JMP (V.15.2.0 Pro, Statistical Discovery Software SAS Inc., Cary, North Carolina, USA) was employed. Normal distribution and homoscedasticity were assessed using Shapiro-Wilks and Levene's tests. Means and standard deviations for age, stature, body mass, BMI, lumbar morphology, and isometric trunk and hip extensor strength parameters were reported. Independent t-tests were used to compare players' age, stature, body mass and BMI between those who did and did not complete strength testing. Where missing data exceeded 5% (Jakobsen et al., 2017) data was imputed by a predictive mean matching approach (Buuren & Groothuis-Oudshoorn, 2011) to be used in the univariable analysis. Player demographics were compared between AFL and NRL. Effect sizes were calculated using Cohen's D and interpreted: trivial <0.2, small 0.2-0.49, large 0.5-0.8 (Cohen, 1988).

Independence of the continuous variables was assessed by Pearson's correlation coefficient and correlation coefficients >0.7 were interpreted as strong and excluded from the multivariable assessment. Separate univariable logistic regression analyses were performed using maximum strength, strength endurance, lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area, quadratus lumborum cross-sectional area, previous non-contact lower limb injury with hamstring strain and knee ligament injury as the dichotomous dependent variable to calculate OR and 95% confidence intervals (95%CI). For strength variables OR are expressed per one standard deviation in produced force. For all other variables OR are expressed per one unit of measure. Alpha level for all analyses was set at $p<0.05$.

Two decision tree models were built to describe the trunk morphological and strength characteristics associated with (i) hamstring strain injuries; and (ii) knee ligament injuries. The independent variables used as predictors included: lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area, quadratus lumborum cross-sectional area, lumbar multifidus to quadratus lumborum ratio, maximum strength, strength endurance and previous injury. Both numerical and categorical data were used to build the decision tree model and for numerical variables the decision tree used an underlying regression algorithm to determine best fitting cut-off values that were used to produce the splits at each node. A G-test was used to measure each nodes' contribution to the -2 log likelihood and log worth expressed as G^2 values. Receiver operator characteristics were used to evaluate the predictive ability of the decision tree model and AUC values calculated. Due to small size of sample no data were held-back for validation.

6.6. Results

6.6.1. Player Demographics and Injury Details

During the 2020 pre-season, 238 professional football players were assessed, 153 players (age 23.2±3.5yr, stature 187.2±7.1cm, mass 93.9±11.7kg BMI 26.8±2.9, 69 AFL, 84 NRL) completed all testing with 126 (age 24.4±3.8yr, stature 187.1±6.4cm, body mass 94.9±11.5kg BMI 27.1±2.8) completing prospective injury follow-up. See figure 19 for flow diagram, and table 9 for player demographics. No significant differences in age, stature, body mass or BMI were found between players with full injury follow-up and players lost to follow-up. Players lost to follow up were significantly heavier (BMI, $p<0.01$), while no differences were observed for other variables. Correlations between continuous variables is shown in table 10 where two (body mass and BMI; quadratus lumborum cross-sectional area and lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio) correlations were above the a priori defined threshold (<0.7).

Figure 19: Flow diagram of participant inclusion and exclusion

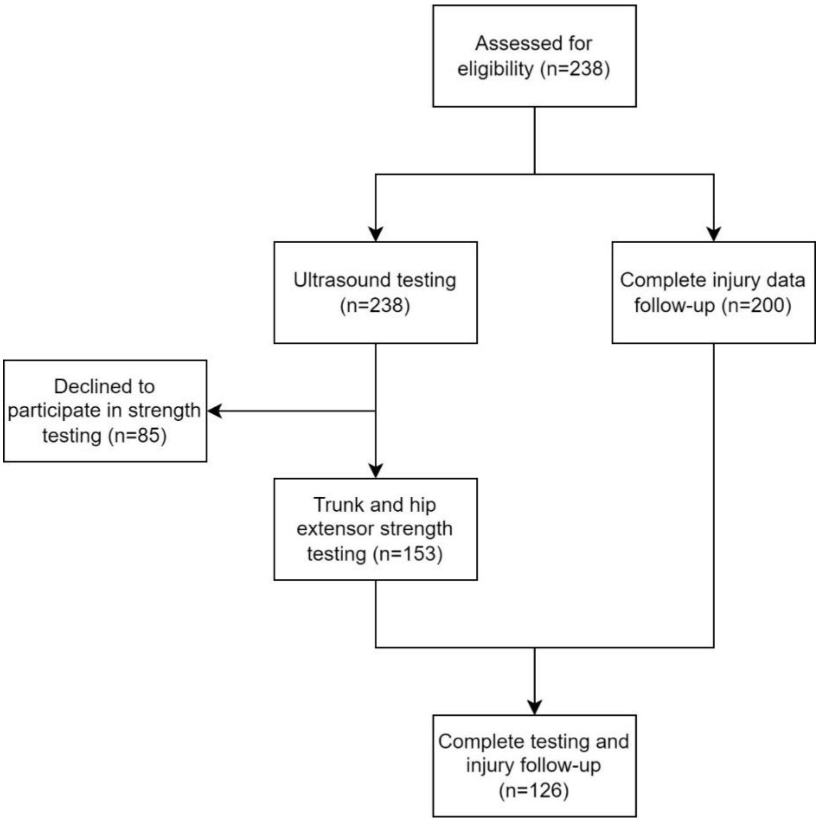


Table 9: Player demographics, LM L5 cross-sectional area, QL cross-sectional area, maximum trunk and hip extension strength and trunk and hip extension strength endurance by football code

	AFL		NRL			
	Mean	**SD**	**Mean**	**SD**	**p-value**	**d**
n	61		65			
Age (years)	23.6	3.6	24.1	3.3	0.269	-0.20
Stature (cm)	188.0	8.1	186.4	5.1	0.195	0.22
Body mass (kg)	86.3	9.4	100.3	9.7	<0.0001*	-1.45
BMI (kg/m^2)	24.4	1.3	28.8	2.3	<0.0001*	-2.37
LM L5 (cm^2)	8.8	1.5	9.5	1.7	0.007*	-0.47
QL (cm^2)	8.2	1.7	8.7	2.1	0.169	-0.24
MAX STR (N/kg)	9.9	2.6	8.2	2.5	0.001*	0.59
STR END (N/kg)	4.2	1.2	3.2	1.3	<0.0001*	0.77

AFL=Australian Football League, NRL=National Rugby League, LM L5 = lumbar multifidus at fifth lumbar vertebrae, QL=quadratus lumborum, n = number of participants, MAX STR = maximum strength, STR END = strength endurance, SD = standard deviation, d = Cohen's d, * represents statistical significance ($p<0.05$)

A total of 84 (67%) players who completed prospective follow-up sustained a non-contact lower limb injury. Nineteen (15%) players sustained a hamstring strain injury, and 13 players a knee ligament injury (11%). Other common lower limb injuries were quadriceps strains (n=6, 5%), calf strains (n=6, 5%), hip/groins (n=6, 5%), Achilles tendons (n=5, 4%), and ankle sprains (n=2, 2%).

Table 10: Correlation (r) matrix between variables used in the injury risk model

	BM	BMI	MAX STR	STR END	L5 CSA	QL CSA	L5/QL
Stature	0.5	-0.1	-0.19	-0.26	0.19*	0.08	0.06
Body mass		0.81	-0.28*	-0.411*	0.38*	0.28*	0.04
BMI			-0.18*	-0.29*	0.3*	0.28*	-0.01
MAX STR				0.64*	-0.01	0.11	-0.12
STR END					-0.14	-0.11	-0.01
LM L5 CSA						0.23*	0.39*
QL CSA							-0.73*

BM = body mass BMI = body mass index, MAX STR = maximum strength, STR END = strength endurance, CSA = cross sectional area, LM L5 = lumbar multifidus at fifth lumbar vertebrae, QL = quadratus lumborum, * denotes statistical significance

6.6.2. Univariable Logistic Regression

Isometric trunk and hip extensor strength measures by injury group with univariable logistic regressions odds ratios are shown in Table 11. Univariable logistic regression analysis showed greater maximum trunk and hip extensor strength endurance (OR: 0.42 per 1 N/kg of measure, 95%CI: 0.23-0.74, p: 0.004, AUC: 0.70) and maximum strength (OR: 0.55 per 1 N/kg of measure, 95%CI: 0.31-0.94, p: 0.039, AUC: 0.64) significantly reduced hamstring strain injury risk. Knee injury risk increased with larger lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area (OR: 1.66 per 1 cm^2, 95%CI: 1.14-2.45, p: 0.008, AUC: 0.65) and larger lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio (OR: 1.57 per 1 unit of measure, 95%CI: 1.13-2.23, p: 0.008, AUC: 0.63). No isometric trunk and hip extensor strength variables were significantly associated with knee ligament injury risk. Imputation of missing lumbar strength data was not different to the presented results.

Table 11: OR, and significance values of univariable logistic regression based on age, previous non-contact lower limb injury, and isometric trunk and hip extensor strength parameters. OR for age per one year and OR for maximum strength and strength

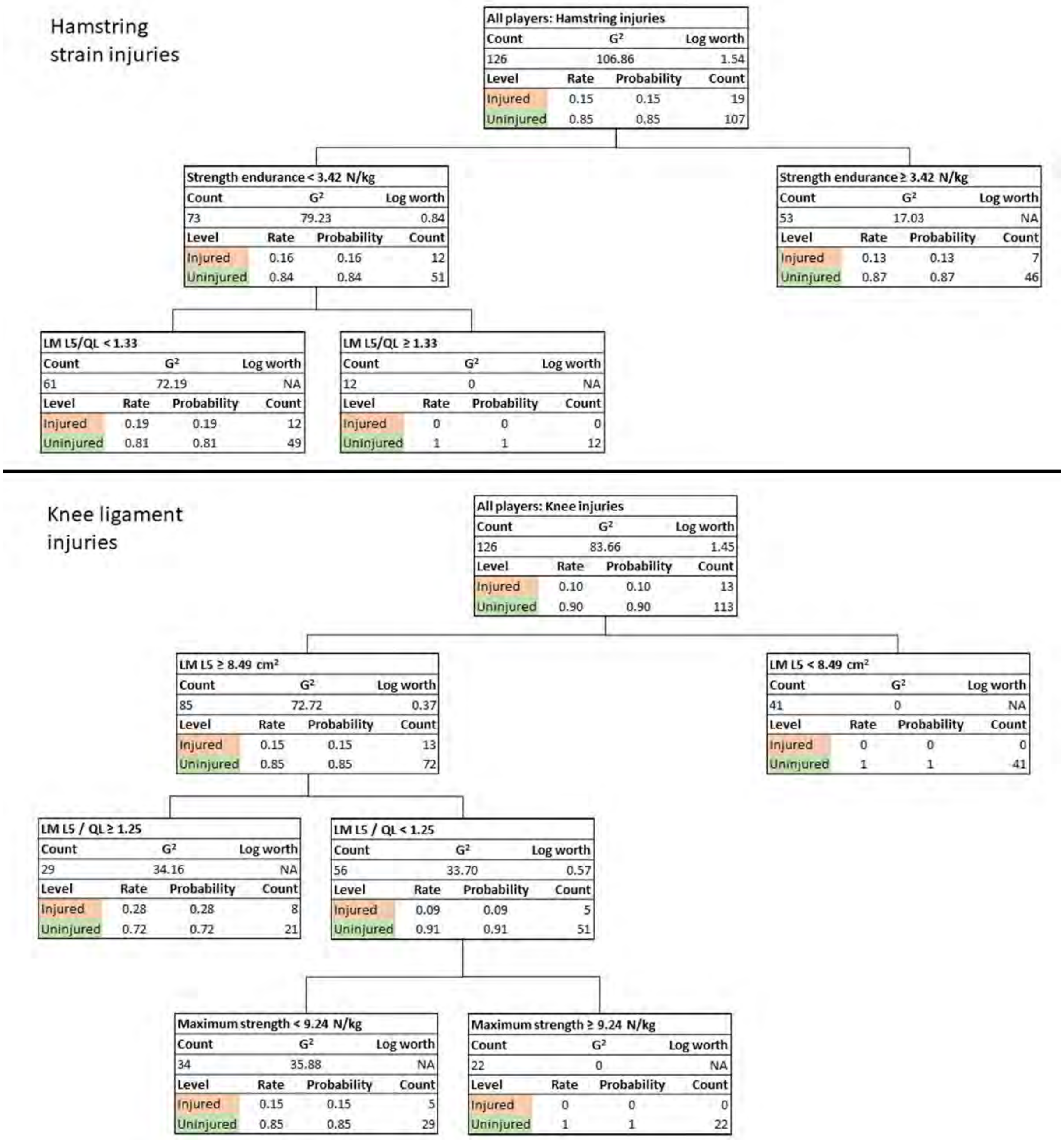
	Hamstring strain injuries							**Knee ligament injuries**						
	Uninjured		**Injured**		**Risk analysis**			**Uninjured**		**Injured**		**Risk analysis**		
	Mean	**SD**	**Mean**	**SD**	**OR**	**95% CI**	**p-value**	**Mean**	**SD**	**Mean**	**SD**	**OR**	**95% CI**	**p-value**
n	**107**		**19**					**113**		**13**				
Previous non-contact lower limb injury	NA	NA	NA	NA	2.19	0.96-4.86	0.056	NA	NA	NA	NA	0.83	0.31-1.94	0.677
Age (years)	23.9	3.9	24.1	3.5	1.01	0.91-1.11	0.859	23.9	4	24.3	3.1	1.03	0.93-1.13	0.595
LM L5 CSA	9.17	1.7	9.15	1.64	0.99	0.67-1.46	0.968	9.05	1.65	9.94	1.79	1.66	1.14-2.45	0.008*
QL CSA	8.56	2.21	8.84	1.89	1.14	0.77-1.67	0.431	8.65	2.2	8.19	1.9	0.8	0.54-1.18	0.272
LM L5/QL	1.14	0.36	1.07	0.26	0.79	0.49-1.20	0.312	1.11	0.31	1.3	0.52	1.57	1.13-2.23	0.008*
MAX STR (N/kg)	9.11	2.65	7.68	2.59	0.55	0.31-0.94	0.039*	8.87	2.59	9.07	3.48	1.11	0.62-1.91	0.721
STR END (N/kg)	3.79	1.31	2.79	1.23	0.42	0.23-0.74	0.004*	3.62	1.31	3.84	1.63	1.19	0.67-2.08	0.540

Abbreviations: NRL=National Rugby League, AFL=Australian Football League, n = number of participants, LM L5 = lumbar multifidus at 5th lumbar vertebrae, QL = quadratus lumborum, CSA = Cross sectional area, MAX STR = maximum strength, STR END = strength endurance * represents statistical significance ($p<0.05$)

6.6.3. Decision Tree Model

Players who sustained a hamstring strain injury were characterised by low strength endurance (< 3.42N/kg). However, protection against hamstring strain injury was observed in players with higher strength endurance (≥ 3.42N/kg) and those with lower strength endurance but high lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio (≥ 1.33). Players who sustained a knee ligament injury were characterised by larger lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area (≥ 8.49 cm^2), larger lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratios (≥ 1.25), and lower maximum strength (< 9.24N/kg) (Figure 20). Protection from knee ligament injury was observed in smaller lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area (< 8.49 cm^2), or in those with a larger lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area (≥ 9.48 cm^2) a low lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio (< 1.25) and higher maximum strength (< 9.24N/kg) provided protection against knee ligament injuries. The decision tree representing hamstring strain injuries pooled across AFL and NRL provided acceptable ROC characteristics (AUC: 0.75) while assessing pooled knee ligament injuries showed an excellent discriminatory effect (AUC: 0.82).

Figure 20: Decision tree plot visualising multivariable contributions to knee and hamstring injury risk. Top tree represents hamstring injuries, bottom tree represents knee injuries. G2 = G2 statistics indicating contribution to -2 log likelihood of each node, L



6.7. Discussion

This study investigated the association between preseason measures of isometric trunk and hip extensor strength, trunk morphology, and subsequent non-contact hamstring strain and knee ligament injuries in AFL and NRL players. Our findings suggest an elevated risk of hamstring strain injury is related to lower isometric trunk and hip extensor maximum strength and strength-endurance. Further, a combination of larger lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area, greater lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio, and lower maximum strength were characteristics of those sustaining a knee ligament injury.

This study is the first to identify a relationship between lower isometric trunk and hip extensor maximum strength and strength-endurance and hamstring strain injury risk. Hamstring strain injuries primarily occur during the terminal-swing phase of high-speed running, where the muscle actively lengthens to decelerate the forward swinging shank. Unaccustomed high-speed running loads (Duhig et al., 2016), low eccentric knee flexor strength, and limited knee flexor strength endurance (Schuermans, Danneels, et al., 2017; Schuermans, Van Tiggelen, et al., 2017), have all been suggested to increase the risk of hamstring strain injury. It is possible that reduced maximum strength and strength-endurance in the trunk and hip extensors may impact the ability of these muscles to cope with the forces experienced during numerous high-speed running efforts over the game's duration. For example, functional magnetic resonance imaging of amateur soccer players has revealed that those with a history of hamstring strain injury display lower metabolic activity from the semitendinosus and a relatively higher reliance on the biceps femoris during a fatiguing leg curl exercise (Schuermans, Danneels, et al., 2017). A prospective follow-up study (Schuermans, Van Tiggelen, et al., 2017) of this cohort demonstrated that this greater reliance on biceps femoris was associated with an increased susceptibility to primary hamstring strain injury in the following 18 months. Subsequently injured players also reached task failure in the leg curl test earlier than those who remained injury free. These observations are at least partly supported by recent sEMG findings, which demonstrated that a disproportionate reliance upon any of the hamstrings was related to limited endurance when 20% of maximal knee flexor force was held until task failure (Avrillon et al., 2018). (Schuermans, Danneels, et al., 2017)It might therefore be argued that intramuscular coordination makes a significant contribution to hamstring fatigue and injury risk.

Knee ligament injuries demonstrated a significant association with lumbar morphology variables. Knee ligament injury risk increased with larger lumbar multifidus muscle at the fifth lumbar vertebral level and lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio. From the decision tree model the combination of larger lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area, greater lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio, and lower maximum strength were characteristic of those who sustained a knee ligament injury. These findings contradict pooled results presented in chapter five where larger lumbar multifidus at the fifth lumbar vertebral level and greater lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio increasing the risk to sustain a non-contact lower limb injury. We therefore reject our hypothesis of smaller lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area being a risk factor for non-contact knee ligament injuries. At the time of writing the authors are usure what reasons cause these contradictory results but the cohort’s different demographics to prior research could be a possible explanation. It must be noted that the receiver operator characteristics for our knee ligament injury models does not show a discriminatory effect to predict knee ligament injuries which limits the validity of our results.

We used univariable logistic regression to identify non-contact hamstring strain and knee ligament injury risk in a pooled cohort of elite athletes from two different competitions (AFL and NRL) that have similar prevalence of hamstring strain and knee ligament injuries. Univariable analyses can provide good estimations of risk associated with a specific factor but fail to explain the multifaceted nature of injury, thus we used a decision tree classification model to describe multivariable associations between trunk and hip extensor strength, lumbar morphology, and hamstring strain and knee ligament injuries. For instance, the decision tree revealed players with greatest risk of sustaining a hamstring injury due to low trunk extensor strength endurance could be protected by greater lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio. Further, the decision tree model showed improved receiver operator characteristics compared to the univariable model in those sustaining a hamstring injury demonstrating that risk assessment can benefit from a comprehensive approach. It is possible to reveal multifactorial and non-linear associations from a larger dataset that might otherwise remain hidden if following the common approach of using univariable logistic regression to identify injury risk in a population.

6.7.1. Limitations

This study included two separate football codes and care should be taken when interpreting the pooled findings given the differences in player characteristics, although pooling was required for statistical power. A second time point for measuring lumbar morphology and strength could have shown changes during the season but this was not achievable due to budget limitations and COVID-19 related travel restrictions. Even though prior research found significant associations between lumbar muscle morphology and lower limb injury risk there remains a gap in the literature as to the exact mechanisms.

Overfitting is one potential issue with decision tree models when selecting the optimal parameter combination. Overfitting is observed when the selected parameter combinations fit too closely with the original training data. To minimise the risk of overfitting, we validated the models using k-fold cross-validation, which splits the original training data into k equal subsets (Fushiki, 2009). Finally, player exposure data was only measured in games and minutes played during the season, but the authors were not provided with GPS based running metrics or training hours for players participating in this investigation.

6.8. Conclusion

This study was the first to identify associations between lower isometric trunk and hip extensor strength and increased hamstring strain injury risk. Increased lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area was related to increased knee ligament injury risk but more research is required into the mechanistic link between knee ligament injuries and lumbar morphology with particular attention to sport specific differences in the populations studied. These findings may guide future injury prevention research programs for both football codes.

6.8.1. Practical Implications

- This study provides a novel trunk and hip extensor strength field test that may assist with identifying hamstring strain injury risk.
- Lumbar morphology combined with trunk and hip extensor strength data improves estimation of hamstring strain injury risk.

- Lumbar morphology combined with trunk and hip extensor strength data not able to improve knee ligament injury risk estimations.

6.9. Acknowledgements

The authors would like to thank the teams (Canberra Raiders, Manly Warringah Sea Eagles, Melbourne Football Club, Melbourne Storm, Port Adelaide Football Club, Sydney West Tigers) and all players who kindly participated in the study.

6.10. Declaration of Competing Interests

M. N. B. is undertaking an MTPConnect REDI Fellowship in collaboration with VALD and has previously received funding from this organisation for research unrelated to the current study. M. D. W. has previously received funding from this organisation for research unrelated to the current study.

The authors state that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

6.11. Funding

This study was funded by an internal Griffith University New Researcher Grant awarded to SD, MB and JH in 2019.

Chapter Seven

Lumbar Multifidus and Quadratus Lumborum Associations with Lower Limb Injury Risk in Team Sports: A Systematic Review and Meta-Analysis

7.1. Publication Statement

This chapter has been submitted and is under review for publication

Hajek, M., Collings, T. J., Roberts L. R., Bourne, M. N., Morris, N. R., Duhig, S. J. (2023). Associations between hamstring strain and knee ligament injuries with isometric trunk and hip strength and morphology in professional Australian rules football and rugby league players. *Unpublished*

7.1.1. Contribution

Martin Hajek's contribution included: study design, data acquisition, analysis, and reporting, interpretation of findings, and writing of the manuscript.

(Signed) [redacted] Date: 28/05/2023

Martin Hajek, PhD candidate

(Countersigned) [redacted] Date: 28/05/2023

Llion Roberts, Co-principal supervisor

7.2. Preface

Following the start of the candidature in 2019 multiple studies investigating associations between lower limb injury risk and lumbar muscle morphology were published which in conjunction with the contribution made in chapter five warranted the conduct of a systematic review. A previous systematic review (Emami et al., 2018) only was able to include three studies investigating lumbar multifidus and quadratus lumborum association with lower limb injuries and was not able to perform a meta-analysis.

7.3. Abstract

Objective To systematically review the literature and synthesise the evidence for lumbar muscle morphology factors for lower limb injury in team field and court sports.

Methods Online databases were searched from inception to February 2023. Eligible studies were prospective in design, analysing lumbar morphology risk factors for lower limb injury. Risk of bias was assessed using the Quality of Prognosis Studies tool and the study was pre-registered with PROSPERO (ID: CRD42020197393) on 06 August 2020

Results Eight studies involving 842 players and 401 lower limb injuries were observed. Five proposed risk factors met the inclusion criteria. Following risk of bias assessment, four studies had high risk of bias while the remaining four were deemed low risk. Overall estimates for smaller lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area (OR=1.15, 95%CI=1.13-1.16) and larger quadratus lumborum cross-sectional area (OR=1.09, 95%CI=1.07-1.10) showed statistically significant associations with lower limb injury risk. In total, five factors were included in the best evidence synthesis, but three could not be included in the meta-analysis. Only quadratus lumborum cross-sectional area showed a consistent strong association with lower limb injury risk, whereas lumbar

multifidus muscle at the fifth lumbar vertebral level asymmetry showed a strong lack of association with lower limb injury risk.

Conclusion The findings may have implications for the use of lumbar multifidus muscle at the fifth lumbar vertebral level and quadratus lumborum cross-sectional area to determine lower limb injury risk in team sport athletes. Conflicting evidence exists for the use of lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area to assess lower limb injury risk. Future work is needed to determine if interventional studies can change these variables and thus influence injury risk.

7.4. Introduction

Non-contact lower limb injuries are prevalent in running-based team sports, negatively impacting individual and team performance (Hoffman et al., 2020) and generating significant financial burden on healthcare systems and sporting organisations (Hickey et al., 2014). The risk of sustaining an injury is influenced by a combination of both modifiable and non-modifiable factors (Meeuwisse et al., 2007). Identification of these factors is an important first step in an evidence-based framework of injury prevention (van Mechelen et al., 1992). A systematic review of the available literature on specific risk factors can thus provide a comprehensive overview over available risk factors for specific injuries.

Small muscle sizes for the lumbar multifidus at the fifth lumbar vertebral level and larger size of the quadratus lumborum, both spanning the lumbar spine (lumbar muscle morphology), have been proposed as a risk factor for non-contact lower limb injuries in team sports (Hides & Stanton, 2017). Typically, muscle morphology is assessed via ultrasound-derived measures of the lumbar multifidus at the fifth lumbar vertebral level and quadratus lumborum (Hides & Stanton, 2017). Measures that have been used to evaluate lumbar muscle morphology include muscle thickness, asymmetry in dimensions, cross sectional area, or alterations in size during contraction. The majority of authors conduct assessments in a prone position while some measure while standing (Roy et al., 2021; Lee et al., 2006; Nandlall et al., 2020) (Lee et al., 2006; Nandlall et al., 2020). This heterogeneity in measurement techniques has potentially contributed to the ambiguity in the relationship between lumbar spine morphology and lower limb non-contact injuries.

A previous systematic review (Emami et al., 2018) sought to consolidate the existing literature by focusing on all trunk muscles and their associations with lower limb injuries. However, it only employed an evidence synthesis approach, without conducting a meta-analysis. The growth of available literature since that review's publication (Emami et al., 2018) and the potential benefits of a meta-analytic approach warrant further investigation. Additionally, the rising integration of lumbar muscle screening into pre-season programs underscores the need for a comprehensive review of current literature.

The aim of this study is to systematically review and synthesise the current literature relating to lumbar multifidus and quadratus lumborum muscle morphology-based risk factors for lower limb injuries in team sports.

7.5. Methods

This review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) guidelines and pre-registered with PROSPERO (ID: CRD42020197393) on 06 August 2020.

7.5.1. *Literature Search*

Online databases PubMed (MEDLINE), Scopus, EBSCOhost (SPORTDiscus), and EMBASE were systematically searched from inception to February 13th, 2023. A comprehensive search strategy was developed according to the PICO framework for prognostic studies (da Costa Santos et al., 2007); **population**: adult team sports athletes, **Indicator**: non-contact, lower limb musculoskeletal injuries, **Comparator**: lumbar spine muscle size mean differences between injured and uninjured groups, **Outcome**: lumbar spine muscle size. Using keywords relating to sports, lumbar muscles, study design, injury types, synonyms, and Medical Subject Headings the final search strategy which was pilot tested to ensure all expected publications were returned within the search.

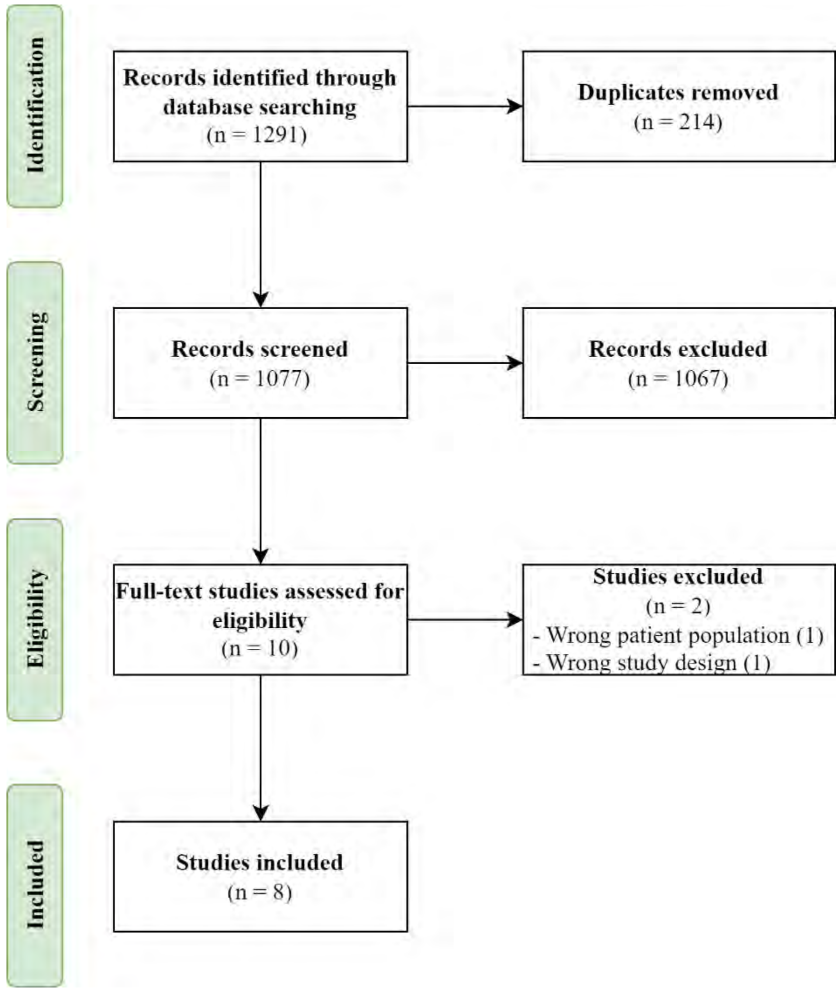
7.5.2. *Study Inclusion / Exclusion Criteria*

Studies were included if they: 1) fulfilled the PICO framework criteria, 2) were a prospective study design, and 3) investigated the association between lumbar muscle size and non-contact lower limb injuries. Studies were excluded if they: 1) were not written in English, 2) were not an original peer-reviewed journal article, 3) were a systematic review, meta-analyse, or letter to the editor, or 4) did not present estimates of risk as either odd ratios, relative risk or group mean and standard deviations.

7.5.3. Article Screening

Screening of articles was performed using the Covidence (Cochrane, London, England) web-based application. Duplicate articles were removed by the application's deduplication tool. Two reviewers (authors MH and TC) independently performed all screening steps of the relevant articles. Articles were initially assessed based on title and abstract and removed if they did not meet the inclusion criteria (Figure 21). Full-text screening was then performed independently by the same two authors with potentially included articles requiring consensus between both reviewers. In the case where no consensus could be reached a third author (SD) would cast the deciding vote. Articles were excluded if they did not meet the inclusion criteria, and the reasons for exclusion recorded (Figure 21).

Figure 21: PRISMA Flow diagram illustrating the identification and selection of studies for the current review.



7.5.4. <u>*Risk of Bias Assessment*</u>

The Quality of Prognosis Studies (QUIPS) tool (Hayden et al., 2013) was used to rate risk of bias in each included study based on six areas: study participation, study attrition, prognostic factor measurement, outcome measurement, study confounding factors, and statistical analysis and reporting. Each of the six sections were answered with a binary response of either; "not likely to increase bias" or "may increase bias". Studies were classified as "low bias" if five of the six sections were classified as "not likely to increase bias", otherwise the study was classified as "high risk" (Table 13). Two reviewers (MH and TC) performed the risk of bias assessment independently. Consensus on final ratings between reviewers was determined by discussion and if needed, consultation with a third reviewer (SD).

7.5.5. Data Extraction

One reviewer (MH) extracted the study characteristics, prognostic factors, and injury outcome data using an Excel spreadsheet (Microsoft Excel, Washington, United States). Data extracted included: first author surname, year of publication, number of participants, number of injuries observed, lumbar morphology data group means and standard deviations, P values, OR, or binary frequency data.

7.5.6. Meta-Analysis

Statistical analyses were performed with the open-source statistical analysis software R (Version 4.03, The R Foundation, Indianapolis, United States) using the "meta" package (Balduzzi et al., 2019). A random effects model was selected for the meta-analysis and heterogeneity quantified using the I^2 statistic and classified as low (<30%), moderate (30% - 50%), substantial (50% - 75%) and high (>75%) (Higgins et al., 2019). If applicable, OR including 95%CI were calculated from binary frequency data, and continuous data were analysed using standardised mean differences (SMD) (Lakens, 2013). Interpretation of SMD was as follows: 0–0.2 = trivial, 0.2–0.5 = small, 0.5–0.8 = medium, and 0.8 or higher = large (Cohen, 2013). Separate meta-analyses were performed for lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area and quadratus lumborum cross-sectional area and their association to subsequent lower limb injuries compared to the uninjured control group. The outcome variables lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area and quadratus lumborum cross-sectional area were selected based on more than two studies investigating them in association with prospective lower limb injuries and providing estimations of risk as the main outcomes.

7.5.7. Best Evidence Synthesis

To summarise findings that were unable to be included in the meta-analysis, a best evidence synthesis was conducted. The best evidence synthesis considers statistical significance, and risk of bias. All lumbar morphology measures reported by a minimum of two studies were included in the best evidence synthesis (Slavin, 1995). Evidence was either characterised as: strong (consistent results in two or more low risk of bias studies, with generally consistent findings in ≥ 75% of studies), moderate (same direction of the risk factor in more than 75% of studies but more than 25% high risk of bias studies), or conflicting (multiple studies, either high or low risk of bias, with consistent results in < 75% studies) (Slavin, 1995).

7.6. Results

7.6.1. Study Characteristics

The initial agreement between reviewers in the article abstract screening process was 88%, with 100% agreement achieved following consensus discussion. Likewise, 100% agreement between reviewers was achieved in the full-text screening process. In total, eight studies (Table 12) were included in the review with a total sample size of 842 and 401 lower limb injuries observed. The median age of the included participants was 22 years (± 1), and mean BMI of 25.1 (± 0.81). Studies included in this review assessed athletes in the following competitions: Australian rules football, cricket, rugby union and rugby league, with Australian rules football being the most common sport where lumbar morphology characteristics were measured.

Table 12: Summary table of all studies included showing participant numbers, mean age, average BMI, sports, level of competition, injuries assessed and outcome measures.

Study	Total number of participants	Number of Injuries	Age (SD)	Height (SD)	Weight (SD)	Participant's sport	Level	Injury type	Outcome measures
Hides 2011	47	12	23 (±3.5)	1.87 (±0.06)	88 (±6.5)	Australian Rules Football	Elite	Hip, Groin and Thigh injuries	LM CSA
Hides 2014	275	191	22 (±3.6)	1.88 (±0.07)	90 (±5.6)	Australian Rules Football	Elite	All lower limb injuries	LM CSA
Hides 2017	102	70	22 (±3.3)	NA	NA	Australian Rules Football	Elite	All lower limb injuries	LM CSA, QL CSA
Olivier 2017	26	11	22 (±1.8)	1.88 (±0.07)	87 (±8.3)	Cricket	Club	All lower limb injuries	LM CSA

Hides 2020	62	20	22 (20, 27)	1.90 (±0.10)	89 (±7.6)	Australian Rules Football	Elite	All lower limb injuries	LM CSA, QL CSA
Roy 2021	21	10	21 (±1.9)	1.71 (±0.08)	75 (±11.1)	Rugby Union	University	All lower limb injuries	LM CSA, LM thickness, LM % change
Hajek 2022	238	72	24 (±3.8)	1.86 (±0.07)	95 (±11.5)	Australian Rules Football and Rugby League	Elite	All lower limb injuries	LM CSA, QL CSA
Low 2023	71	15	16 (±0.7)	1.82 (±0.07)	86 (±13.4)	Rugby Union	Junior	All lower limb injuries	LM CSA

Abbreviations: SD=Standard deviation, LM=lumbar multifidus, QL=quadratus lumborum, CSA=cross-sectional area

7.6.2. Risk of bias assessment

Individual assessments of the risk of bias using the QUIPS tool resulted in four studies being classified as low risk and four studies classified as high risk of bias (Table 13). Overall agreement between both reviewers was 90% with full consensus (100%) following discussion. Failure to address study confounders was the most frequently exhibited source of bias (n=5) followed by using invalid or unreliable outcome measures (n=3).

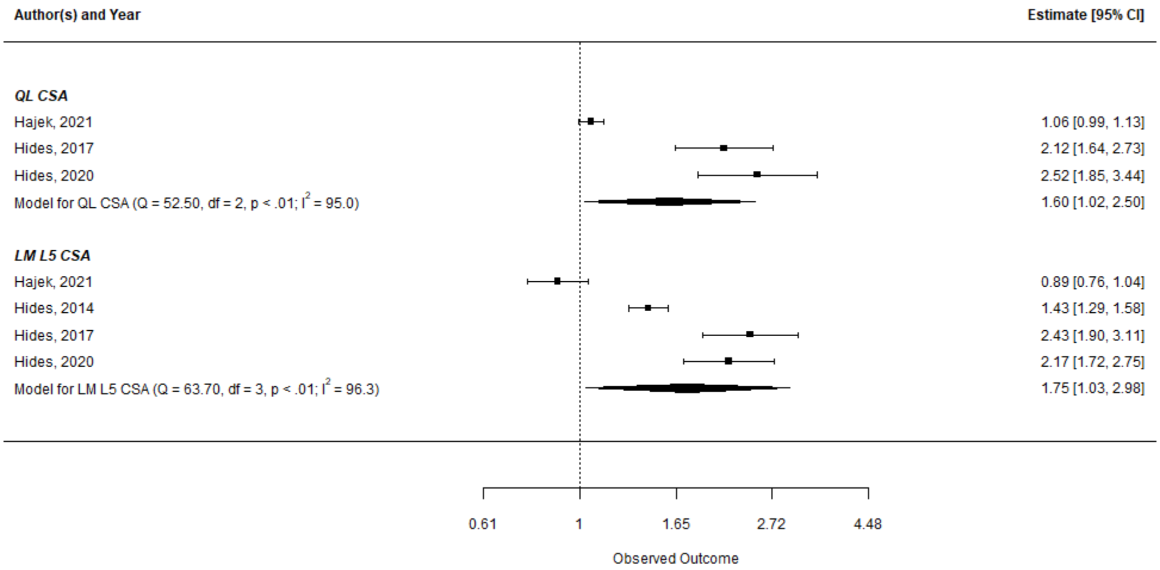
Table 13: Quality of prognostic studies (QUIPS) risk of bias assessment for included studies.

Study	Participation	Attrition	Prognostic Factor	Outcome Measure	Confounders	Statistical Analysis	Overall
Hides 2011	High	Low	Low	Low	High	High	High risk
Hides 2014	Low	Low	Low	High	High	Low	High risk
Hides 2017	Low	Low	Low	Low	High	Low	Low risk
Olivier 2017	Low	Low	Low	High	High	Low	High risk
Hides 2020	High	Low	Low	Low	Low	Low	Low risk
Roy 2021	Low	Low	Low	Low	Low	Low	Low risk
Hajek 2022	Low	Low	Low	Low	Low	Low	Low risk
Low 2023	Low	High	Low	High	High	High	High risk

7.6.3. Meta-Analysis

Smaller lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area (OR=1.15, 95%CI=1.13-1.16) (Hajek et al., 2022; Hides et al., 2020; Hides & Stanton, 2017; Hides et al., 2014) and larger quadratus lumborum cross-sectional area (OR=1.09, 95%CI=1.07-1.10) (Hajek et al., 2022; Hides et al., 2020; Hides & Stanton, 2017) were significantly associated with increased odds of prospectively sustaining a lower limb injury (Figure 22). Large heterogeneity (95.0 and 96.3%) was observed in both meta-analyses.

Figure 22: Random effects meta-analyses of quadratus lumborum and lumbar multifidus (lumbar vertebrae 5) cross-sectional area and risk of lower limb injury. Risk estimate in odds ratios for lumbar multifidus are in opposite direction, indicating that smaller lumbar multifidus size indicates higher risk.



Abbreviations: QL=quadratus lumborum, CSA=cross-sectional area, LM L5=lumbar multifidus at fifth lumbar vertebral level

7.6.4. <u>*Best Evidence Synthesis*</u>

In total, five factors were included in the best evidence synthesis (Table 14), three of which could not be included in the meta-analysis. Only quadratus lumborum cross-sectional area showed a consistently strong association with lower limb injury risk, and lumbar multifidus muscle at the fifth lumbar vertebral level asymmetry showed a strong lack of association with lower limb injury risk. Conflicting evidence for an association with injury risk was demonstrated by lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area, lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area to quadratus lumborum cross-sectional area ratio and lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area < quadratus lumborum cross-sectional area.

Table 14: Best evidence synthesis for lumbar morphology risk factors

Proposed risk factor	Number of studies	Level of evidence	Association	No association
LM L5 CSA	4	Conflicting	(Hides et al., 2020; Hides et al., 2011; Hides & Stanton, 2017; Hides et al., 2014)	(Hajek et al., 2022; Roy et al., 2021)
QL CSA	3	Strong association	(Hajek et al., 2022; Hides et al., 2020; Hides & Stanton, 2017)	
LM L5 CSA / QL CSA	3	Conflicting	(Hides et al., 2020; Hides & Stanton, 2017)	(Hajek et al., 2022)
LM L5 Asymmetry	3	Strong no association		(Hides et al., 2014; Olivier et al., 2017; Roy et al., 2021)
LM L5 CSA < QL CSA	2	Conflicting	(Olivier et al., 2017)	(Hajek et al., 2022)

Abbreviations: LM L5=lumbar multifidus at fifth lumbar vertebrae, QL=quadratus lumborum, CSA=cross-sectional area

7.7. Discussion

This systematic review and meta-analysis evaluated the literature on lumbar muscle morphology as a risk factor for lower limb injuries, finding significant associations between smaller lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area and larger quadratus lumborum cross-sectional area with increased lower limb injury risk. However, only larger quadratus lumborum cross-sectional area demonstrated a strong association with injury risk, while lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area showed conflicting results. These findings expand on previous research and highlight the need for further investigation into the associations between lumbar morphology, injury risk, and potential injury risk reduction strategies.

The most assessed parameter is the lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area in a prone position, using ultrasound imaging, which was evaluated in all but one of the studies included in this review. The association between smaller lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area and lower limb injuries was first reported in Australian football players (Hides et al., 2011) and subsequent studies by the same research group confirmed these findings (Hides et al., 2020; Hides & Stanton, 2017; Hides et al., 2014). However, no other investigations have replicated these results in different populations, including cricket (Olivier et al., 2017), rugby union (Low et al., 2023; Roy et al., 2021) and rugby league (Hajek et al., 2022). While the meta-analysis performed in this review revealed a significant overall association between lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area and subsequent lower limb injury risk, only four studies (Hajek et al., 2022; Hides et al., 2020; Hides & Stanton, 2017; Hides et al., 2014) could be included in the meta-analysis since the other investigations did not use statistical models that quantify injury risk. Including all studies that assessed lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area and subsequent lower limb injury in a best-evidence synthesis demonstrated conflicting evidence for this parameter. The studies included in the meta-analysis were largely performed by the same research group in Australian Football, revealing consistent results. However, other studies in cricket, rugby league, and rugby union did not demonstrate the same associations, suggesting lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area as a risk factor for subsequent lower limb injury may not be generalisable to other sports. Overall, the existing evidence suggests a significant association between smaller lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area and increased risk of non-contact lower limb injuries in team-based field and court sports. Caution is required when applying these results to sports outside of Australian rules football and small overall effect sizes that might not be meaningful.

The current review revealed strong evidence for an association between quadratus lumborum cross-sectional area and lower limb injury risk. Both the meta-analysis and best evidence synthesis revealed consistent results indicating that increased quadratus lumborum cross-sectional area may be a factor for estimating lower limb injury risk. The evidence is limited by the fact that only three studies (Hajek et al., 2022; Hides et al., 2020; Hides & Stanton, 2017) used the quadratus lumborum cross-sectional area variable in their investigation and a lack of clear mechanism by which the increased quadratus lumborum cross-sectional area may increase injury risk. Future work is needed to determine how larger cross-sectional area of a trunk muscle is related to increased lower limb injury risk.

While measures of lumbar morphology in isolation may provide an association with lower limb injury risk, this approach is limited by critical issues. Firstly, there is no clear rationale in the literature to explain why smaller lumbar multifidus muscle at the fifth lumbar vertebral level or larger quadratus lumborum size would lead to increased lower limb injury risk. Previous investigations (Hides et al., 2020; Hides & Stanton, 2017; Hides et al., 2014) have based their rationale on either a deficit in hip abduction and external rotation strength and/or anterior, posterior and lateral trunk muscle endurance (Leetun et al., 2004), or reduced neuromuscular control of the trunk (Zazulak et al., 2007a). While neuromuscular control of the trunk may be contributing to lower limb injury risk, and the lumbar multifidus being a muscle that is highly involved in the reflex control of the spine (Nitz & Peck, 1986a), it remains unclear if muscle cross-sectional area would be the main contributor to any of the aforementioned parameters. Secondly, reducing lower limb injury risk to a few select variables limits all studies included in this review. Lower limb injury risk is based on multiple modifiable and non-modifiable risk factors that interact with each other in a non-linear fashion, requiring more complex approaches when attempting to estimate injury risk (Ruddy et al., 2019). Variables can be associated with lower limb injury risk without having any causal relationship most likely because many confounding variables are not accounted for.

7.7.1. Limitations

The major limitation of this systematic review and meta-analysis was a relatively small sample size with only half of the available studies being able to be included in the meta-analysis, which may overestimate the effects and lead to inaccurate heterogeneity statistics. Further, half of the included publications showed a high risk of bias, typically resulting from a failure to address confounding variables or the use of inadequate or unreliable outcome measures. The failure to address confounding variables introduces another layer of uncertainty to the presented results as it can be impossible to determine if the outcome is due to confounders or the main variable. The inconsistencies or adequacy of the used outcome measures makes comparison of the results between studies difficult and with high participant heterogeneity the overall results of this review are severely limited. Additionally, in all studies, the risk factors were only measured in pre-season or at the beginning of the playing season with the injuries often occurring months after initial data collection. Finally, all included studies grouped a wide range of injury types together which have different injury mechanisms and no subgroup analyses were possible due to lack of reported subgroups in the included studies.

7.7.2. Future Directions

To strengthen the evidence supporting the potential link between lumbar muscle morphology and lower limb injury risk, future work should incorporate low-bias studies and refine the methodology for assessing lumbar muscles. To effectively address methodological limitations, larger studies are needed that regularly evaluate outcome variables throughout the entire sports season. Furthermore, adopting multivariable approaches can better capture the complex nature of sports injuries and account for additional confounding factors.

7.8. Conclusion

The findings of this systematic review and meta-analysis suggest that larger quadratus lumborum cross-sectional area is associated with increased lower limb injury risk, while factors related to lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area showed conflicting evidence. The findings may have implications for the use of lumbar multifidus muscle at the fifth lumbar vertebral level and quadratus lumborum cross-sectional area to determine lower limb injury risk, but future research is required for specific injury subgroups and needed to determine if interventional studies can change these variables and thus influence injury risk.

Compliance with Ethical Standards

Funding No funding was received to conduct this review.

Conflicts of interest/Competing interests Martin Hajek, Tyler Collings, Llion Roberts, Matthew Bourne, Norman Morris and Steven Duhig declare that they have no conflicts of interest relevant to the content of this review.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Code availability Not applicable.

Availability of data and materials Not applicable

Author contributions MH, SD, MB, LR and NM contributed to the review design. MH, TC and LR performed the literature screening. MH and TC performed the risk of bias assessment. All authors contributed to the writing of the manuscript.

Chapter Eight

General Discussion

The purpose of this thesis was to investigate whether size measurements of muscles spanning the lumbar spine; lumbar multifidus and quadratus lumborum, combined with assessments of lumbar muscle strength, could estimate non-contact lower limb injury risk in team sports. This research builds on preliminary evidence suggesting smaller lumbar multifidus and larger quadratus lumborum muscles were associated with an increased risk of sustaining a subsequent lower limb injury in Australian Football players (Hides et al., 2020; Hides et al., 2011; Hides & Stanton, 2017; Hides et al., 2014). Although earlier findings are promising, there are key limitations to their generalisability. Firstly, previous studies have only focussed on single sports cohorts with mostly small sample sizes and are lacking cross-sport analyses. Secondly, most of the existing literature has been conducted in Australian rules football, leaving uncertainties about the applicability of these findings to other sports. Thirdly, past studies have only addressed lumbar muscle morphology as the main variable for their analysis, potentially neglecting confounding variables. Lastly, the aetiology of the association between lumbar muscle morphology and lower limb injury risk remains unclear. This thesis aimed to provide a more comprehensive understanding of this relationship by quantifying lumbar muscle strength in conjunction with lumbar muscle morphology. To achieve this objective, the individual chapters of this thesis aimed to 1) assess the reliability of ultrasound-derived measurements of lumbar multifidus and quadratus lumborum morphology, 2) confirm lumbar morphology as a risk factor for non-contact lower limb injuries in Australian rules football and rugby league, 3) develop a novel lumbar strength test and evaluate its reliability, 4) prospectively determine if non-contact lower limb injuries can be more accurately predicted using a combined measure of lumbar morphology and strength, and 5) systematically review the literature examining the relationship between lumbar muscle morphology and lower limb injuries.

8.1. Summary of Main Findings

The reliability study was the first to assess intra- and inter-rater reliability of cross-sectional area of the quadratus lumborum via ultrasound imaging collected from a sample of 10 healthy, recreationally active participants. Calculated values for ICC and CV all showed excellent reliability for both between-session and between-rater measurements of lumbar multifidus muscle at the fifth lumbar vertebral level and quadratus lumborum muscles (Chapter four). A replication study, based on the predictive model described by Hides and Stanton (2017), examined the ability of lumbar muscle morphology measurements to estimate non-contact lower limb injury risk. These findings showed limited capacity of lumbar muscle morphology measures to estimate lower limb injury risk in a cohort of Australian rules football and rugby league players. While increased quadratus lumborum cross-sectional area was replicated as a risk factor for non-contact lower limb injury in the Australian rules football population, this association was not found for lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area nor the affiliated lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio. No significant associations between lumbar muscle morphology and non-contact lower limb injury risk were found in the rugby league cohort. These data may suggest football code specific injury risk factors (Chapter five).

A novel field test was developed to assess isometric trunk and hip extensor strength by modifying the Sorensen test and incorporating a 65-second strength assessment using a ground-mounted load cell to quantify isometric force production. Strength testing data, normalised to participant body mass, demonstrated excellent between session reliability based on ICC and CV values (Chapter four). A large-scale prospective study investigated the association between preseason measures of isometric trunk and hip extensor strength, lumbar muscle morphology, and subsequent non-contact hamstring strain and knee ligament injuries in Australian rules football and rugby league players. The findings suggest an elevated risk of hamstring strain injury is related to lower isometric trunk and hip extensor maximum strength and strength-endurance. Further, a combination of larger lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area, greater lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio, and lower maximum strength were characteristics of those sustaining a knee ligament injury (Chapter six).

Lastly, a systematic review and meta-analysis synthesised the literature on lumbar muscle morphology as a risk factor for lower limb injuries. A systematic review was published in 2018 (Emami et al., 2018) investigating Associations between trunk muscles and lower limb injuries just before the start of the candidature and with more new evidence being released since the start of the candidature (Hides et al., 2020; Low et al., 2023; Roy et al., 2021) a decision was made to systematically review the literature after conducting the experimental studies (Chapters five and six). The review included a total of 842 players from eight prospective studies that examined the association between preseason measures of lumbar muscle morphology and subsequent lower limb injury. Smaller lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area and larger quadratus lumborum cross-sectional area were significantly associated with increased lower limb injury risk in the meta-analysis. Only larger quadratus lumborum cross-sectional area had a strong association with subsequent lower limb injury risk while lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area showed conflicting results in the best evidence synthesis. Other lumbar morphology measures were not associated with lower limb injury risk or had conflicting evidence. These findings indicate associations between lumbar morphology and injury risk that warrant further investigation with potential implications for injury risk reduction interventions and pre-season screening.

8.2. Synthesis and Interpretation of Main Findings

8.2.1. <u>Lumbar muscle morphology as a risk factor for lower limb injuries in elite team sports</u>

The study presented in chapter five aimed to replicate a predictive model by Hides and Stanton (2017) in a large prospective cohort comprised of elite Australian rules football players and rugby league players. This was the first study attempting to replicate the findings by Hides and Stanton (2017) in a heterogenous cohort and found that only larger quadratus lumborum cross-sectional area was a risk factor for lower limb injuries in the Australian rules football players included. No statistically significant associations were found between rugby league players and lumbar multifidus or quadratus lumborum cross-sectional area and asymmetry of the lumbar multifidus also did not show any statistically significant associations with lower limb injury risk. Based on the presented results in Chapter five and studies by Roy et al. (2021) and Olivier et al. (2017) it can be suggested that lumbar morphology variables are a risk factor only specific to Australian rules football which could be related to the specific demands of the sport. The higher amount of jumping and landing tasks in Australian rules football compared to rugby league, rugby union and cricket in addition to players having a different physiological profile by being significantly taller and lighter potentially contributes to the different results seen in this cohort.

In addition, our results presented in chapter six are the first to show an association between larger lumbar multifidus muscle at the fifth lumbar vertebral level size and prospective knee injury risk. Contrary to our hypothesis, larger lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area and larger lumbar multifidus muscle at the fifth lumbar vertebral level to quadratus lumborum ratio were associated with an increased risk of sustaining a knee ligament injury. The mechanism(s) underpinning this association remain unclear but might be related to lumbopelvic stability during high-risk tasks (e.g., cutting and landing) (Collings et al., 2022) or could be caused by certain tibial movement patterns that cause increased strain in the ACL (Quatman et al., 2011). However, this subgroup analysis pooled all types of non-contact knee ligament injuries (Bahr & Holme, 2003), which likely had a range of different mechanisms. No statistically significant associations were found between any lumbar muscle morphology variables and the risk of sustaining a hamstring strain injury and due to small sample sizes, it was not possible to assess other injury specific subgroups.

The preliminary evidence by Hides et al. (2011) suggested an association between smaller muscle size of the lumbar multifidus and hamstring, groin, and thigh injuries. Due to the exploratory nature of this study, there was no attempt to accurately estimate subsequent injury risk based on cross-sectional area of the lumbar multifidus and only an analysis of variance was performed to compare injured and uninjured players in this cohort. Subsequent studies by the same research group found consistent results in the same population and incorporated estimations of injury risk in their study design (Hides et al., 2014). Smaller lumbar multifidus muscle at the fifth lumbar vertebral level and larger quadratus lumborum were shown to increase lower limb injury risk in this cohort, and a smaller ratio between those muscles was also identified to be a predictor for injury risk (Hides et al., 2020; Hides & Stanton, 2017).

Other research groups have investigated lumbar multifidus and its relation to increased lower limb injury risk. In a cohort of South African cricket fast bowlers, increased asymmetry between the dominant and non-dominant side of the lumbar multifidus was present in players suffering from lower back pain but no statistically significant difference was found in players that sustained a lower limb injury (Olivier et al., 2017). Another study in Canadian collegiate rugby union players found that reduced ability to isometrically contract the lumbar multifidus under real-time ultrasound imaging showed an association with increased lower limb injury risk during the pre-season but not during the playing season. lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area and asymmetry were not found to be significantly associated with increased lower limb injury risk (Roy et al., 2021). Both studies had low sample sizes but were the first attempts to estimate injury risk based on lumbar morphology outside of the Australian rules football. These findings, in addition to the current results suggest limited generalisability of lumbar multifidus size as a risk factor.

In general, larger cross-sectional area of the quadratus lumborum during pre-season testing appears to be significantly associated with the risk of sustaining subsequent non-contact lower limb injuries. Preliminary evidence, in conjunction with the replication study (Chapter four), demonstrated that larger quadratus lumborum cross-sectional area was significantly associated with prospective non-contact lower limb injury risk. Both the meta-analysis and best evidence synthesis presented in chapter seven also confirmed quadratus lumborum cross-sectional area to be a risk factor for non-contact lower limb injuries. Since larger size of the quadratus lumborum increased the injury risk in elite Australian rules football and rugby league players, following the injury prevention model by Finch (2006) can prove problematic because any interventional studies would have to be targeted towards reducing muscle size in the quadratus lumborum, presenting an obstacle in the translatability of the findings to actively reduce injury risk. A possible explanation for this fact is the significant correlation between quadratus lumborum cross-sectional area and BMI (Chapter two) with higher BMI suggested as a risk factor for lower limb injuries (Bojicic et al., 2017). In contrast, a smaller lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area demonstrated a significant association with lower limb injury risk in the meta-analysis (Chapter seven), suggesting this rick factor could be mitigated through targeted interventions. However, more recent studies (Low et al., 2023; Olivier et al., 2017; Roy et al., 2021) could not confirm lumbar multifidus muscle at the fifth lumbar vertebral level's association with lower limb injury risk in cohorts beyond elite Australian rules football players. To substantiate the relationship between lumbar muscle morphology and lower limb injury risk, interventional studies are essential, and there is a pressing need for investigations into the underlying mechanisms linking lumbar muscles and lower limb injury risk.

8.2.2. Trunk and Hip Extensor Strength and its Association with Lower Limb Injuries

One of the main aims was to develop a reliable field test for measuring trunk and hip extensor muscle maximum strength and strength endurance and to evaluate its potential associations with prospective non-contact lower limb injuries. The novel test developed in Chapter four is based on the Sorensen test (Biering-Sorensen, 1984) which requires a plinth, load cell, harnesses, and weight plates in a gym which can be performed at any professional club's facility in a time efficient manner. A previously published testing protocol (Corin et al., 2005) was used to determine trunk and hip extensor muscle maximum strength (5s MVIC) and strength endurance (45s MVIC) with a load cell used to quantify force generation. The novel trunk and hip extensor strength test demonstrated excellent reliability (Chapter four).

A trunk and hip extension strength test was selected due to the lumbar multifidus's and quadratus lumborum's involvement in trunk extension that was shown in previous EMG studies (B. Jonsson, 1970; Macintosh & Bogduk, 1986; Morris et al., 1962a) and given the suggested association with players ability to isometrically contract their lumbar multifidus and increased lower limb injury risk (Roy et al., 2021). Results presented in Chapter six indicates a prospective association between lower trunk and hip extensor maximum strength and strength endurance and increased hamstring strain injury risk. However, no significant associations were found between trunk and hip extensor strength and knee ligament injuries. Since it is not possible to isolate trunk extensor muscles in a strength test setting, involvement of hip extensor and knee flexor muscles must be expected in the proposed modified Sorensen test which could explain the association with hamstring strain injury risk (Green et al., 2020). Incorporating the values of trunk and hip extensor strength combined with lumbar muscle morphology into a multivariable decision tree model was able to improve the estimation of hamstring strain and knee ligament injury risk by increasing sensitivity and specificity of the predictive model. Additionally, a recent systematic review found significant associations between lateral trunk flexion strength and lower limb injury risk (Collings et al., 2021). Overall, the proposed trunk and hip extensor strength test could be used in a time efficient manner to collect data from seven professional football clubs, demonstrated excellent reliability and showed an association with increased hamstring strain injury risk. Future work is needed to determine if interventions that increase trunk and hip extensor strength reduce hamstring injury rates.

8.2.3. *Potential Mechanisms Causing Associations Between Lumbar Muscles and Lower Limb Injuries*

The most suggested mechanism for lumbar multifidus influencing lower limb injury risk is based on the role of the muscle acting as a spinal stabilising muscle. The density of muscles spindles in the lumbar multifidus makes it an important part of the reflex arc and it is hypothesised that the muscle thus provides a proprioceptive input. An investigation by Zazulak et al. (2007b) into the association between trunk reflex control and prospective knee ligament injury risk in American collegiate athletes was cited as rationale for this argument. Notably, the study only revealed increased knee injury risk for female athletes that had impaired reflex control and did not find increased risk for male athletes. To explain an association between smaller lumbar multifidus size and increased lower limb injury risk with the muscle's implication in reflex control an investigation into the function of the lumbar multifidus in relation to its size is required. Muscular strength is one component of muscular function but might not be the most relevant parameter to assess with regards to lower limb injury risk, and muscle reflex control could be more indicative. Australian rules football requires more jumping and landing than rugby union, rugby league, or cricket (Saw et al., 2018) where postural stability of the spine might play an important part (Chuter & Janse de Jonge, 2012). A limited number of studies showed that landing kinematics could be altered after strength training (Araujo et al., 2015; Martinez et al., 2018) or technique instructions (Chijimatsu et al., 2020) but to date, the available literature is inconclusive. Assessing muscle size or isometric strength alone will not be sufficient to test if lumbar stability is associated with lower limb injury risk and future testing should assess dynamic lumbar muscle function under unanticipated perturbations.

8.3. Strengths and Limitations

One of the key strengths of the research presented in this thesis is the inclusion of a large cohort from two separate sports (Australian rules football and rugby league), making this the first study to assess lumbar muscle morphology and strength in two separate cohorts, which enhances the generalisability of the results. One part of this thesis (Chapter five) focussed on replicating a previously established injury prediction model in a separate cohort, a step crucial in the scientific method of predicting injuries (Finch, 2006) that is frequently overlooked. Additionally, the novel trunk and hip extensor strength test should allow for a more widespread assessment of trunk and hip extensor strength in athletes that can contribute to creating a comprehensive athlete profile.

Specifically, the prospective studies presented in this thesis (Chapter five and six) are limited by the fact that measurements with elite Australian rules football and rugby league players were only conducted at a single timepoint during the preseason and it is unknown weather lumbar muscle morphology or strength change over time. Based on previous evidence it can be expected that size of the lumbar multifidus decreases during the playing season, (Hides et al., 2014) but it is unknown if this change affects injury risk. Changes of lumbar muscle strength over the course of the playing season have not yet been assessed and strength measurements are expected to fluctuate over time leading to uncertainty of the lumbar strength at the time of injury. Therefore, there is a need to increase the total sample size to observe more injuries and allow for more subgroup analyses and increase the number of timepoints at which outcome variables are assessed. It can be beneficial to measure different outcome variables directly related to the injury mechanisms, but this will increase the complexity of the research and affect feasibility.

Research into risk factors of lower limb injuries does not come without limitations, mainly that all results are based on associations and not causal inference. Many present studies pool different types of lower limb injuries that have a variety of mechanisms and measuring their association to a risk factor. The sample size included in the prospective studies did not allow for subgroup analyses past hamstring strain and knee ligament injuries (the most common and severe injuries, respectively) and future studies with larger numbers of participants are required to assess other injury types. It is unknown if measures of lumbar morphology or strength collected during the preseason are directly related to an injury sustained in an elite competition and therefore, if altering a measure through exercise will change the related injury risk. More regular strength measurements could provide a better estimation for lower limb injury risk although a study investigating hamstring strain injury risk did not see an improvement in injury prediction through increased measurement time points (Opar et al., 2022). Further work is required to identify causal relations and test body segments directly involved in the injury mechanism or muscles commonly affected by strain injuries. It can be argued that a mechanistic relationship exists between the proposed trunk and hip extensor strength test and hamstring strain injuries due to the expected hamstring involvement in the test. Randomised controlled trials targeted at changing a risk factor need to be conducted to test if injury rates can be lowered through exercise programmes (Bahr & Holme, 2003). No currently available screening test can predict injury risk on an individual level (Bahr, 2016) and more research needs to assess if injury screening can be used to guide training interventions.

Trying to estimate lower limb injury risk based on a univariable approach may not be possible due to a high degree of simplification in the model (Ruddy et al., 2019). Complex and non-linear interactions between modifiable and unmodifiable risk factors contribute to injury risk (Bahr & Holme, 2003) in elite sports and generating datasets that are large enough is a hurdle for injury risk factor research. The prospective study (Chapter six) tried to address this issue by aiming to combine lumbar muscle morphology and trunk and hip extensor strength and using a machine learning approach (decision tree model) but this will still only account for a limited proportion of the total lower limb injury risk. Collaborative efforts between researchers of different specialisations should be made to form a more comprehensive dataset of variables relevant to lower limb injuries in elite Australian rules football and rugby league players.

8.4. Practical Implications

The preseason screening tests assessed in this thesis (ultrasound imaging for lumbar muscle morphology and trunk and hip extensor strength) have demonstrated to be fast and reliable measures that can be done in the setting of elite Australian rules football and rugby league players and can be included in a comprehensive risk profile. Screening lumbar muscles with ultrasound imaging is an established technique that has been validated against a gold standard (Hides et al., 1995) and the Sorensen test is a well-established, reliable and valid measure for trunk and hip extensor endurance (Demoulin et al., 2006). Lumbar morphology and trunk and hip extensor strength alone might not be the most accurate ways to estimate lower limb injury risk and incorporating them in a more complex model may provide more accurate results. Especially measures of trunk control could add insight to existing lower limb injury risk models.

Many professional clubs perform regular preseason injury screenings, and the findings of this thesis can help to improve how this process is conducted. Only scanning the cross-sectional area of the lumbar multifidus has not shown to provide practitioners with the most consistent estimations for non-contact lower limb injury risk. A combined approach measuring cross-sectional area of both lumbar multifidus and quadratus lumborum in conjunction with measures of muscle function (e.g.: lumbar muscle strength or contractile ability of lumbar muscles) can be used to create a comprehensive risk profile of the athlete.

8.5. Recommendations for Future Research

Future research could aim to compare the novel trunk and hip extensor test to a selection of exercises targeting lumbar back muscles to assess its ability to elicit MVIC in the target population. Subsequently, an exercise programme can be developed and assessed for its efficacy for increasing trunk and hip extensor maximum strength and strength endurance and its effect on injury risk. Ideally, future studies with larger numbers of participants should include a greater duration longitudinal study design and measuring outcome variables at multiple time. Studies using a mechanistic approach should be conducted to investigate if lumbar muscle morphology is related to neuromuscular control of the trunk and if lower limb injury risk can be influenced through changes in trunk kinematics.

8.6. Conclusion

The main conclusions that can be drawn on the basis of the research presented in this thesis are that i) smaller lumbar multifidus muscle at the fifth lumbar vertebral level cross-sectional area was identified as a risk factor for lower limb injury risk in a systematic review but could not be confirmed in a prospective study; ii) larger quadratus lumborum cross-sectional area is a risk factor for subsequent lower limb injury in AFL player, as evidenced in the systematic review and prospective study; iii) trunk and hip extensor strength is associated with hamstring strain injury risk; and iv) combining measures of lumbar muscle morphology with trunk and hip extensor strength increased the specificity and sensitivity of the lower limb injury risk estimation model. Results of this thesis may inform targeted training to reduce injury risk in elite Australian rules football and rugby league players but randomised controlled trials are required to measure the capacity to modify injury risk.

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Appendix

10.1. Appendix 1: Informed Consent Form

Exploring the relationship between trunk extensor morphology and strength with lower back pain and leg injury risk in elite rugby league and Australian rules football players

INFORMATION SHEET

Who is conducting the research

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Why is the research being conducted?

Within Australian football codes, lower back pain appears to occur more frequently and severely than the non-athletic population and it has been proposed that those experiencing this issue may have a higher risk of subsequent lower-limb injury. We

aim to further understand lower back pain and consequently reduce lower limb injury risk.

What you will be asked to do

Should you wish to participate in this study, you will be required to attend one session at your training facility. A few invited participants will be invited to attend a second session to determine reliability, Multifidus and quadratus lumborum will be collected via ultrasound techniques and require participants lie prone on a plinth. Strength tests take ~1min to complete per test and the trunk muscle imaging takes 8-10min. All subsequent lower back pain (LBP) and leg injuries will be recorded by the club's medical team and provided to the researchers at the end of the 2020 season for inclusion in this research. Researchers may take photos as a means of explaining methods, you will be asked for consent before any images are taken and used.

The basis by which participants will be selected or screened

Athletes will not be included should they have deemed unfit by the club's physiotherapist.

The expected benefits of the research

This research should provide information that assists in reducing the prevalence of lower back pain and injury incidence within rugby league and Australian rules football.

Risks to you

There is a degree of associated risk with any maximal muscle exertion. However, these

assessments are identical to those performed in weight training sessions you have previously experienced. Furthermore, you have the opportunity to familiarise yourself with the protocol before performing subsequent maximal contractions. Should you experience pain or muscle strain as a consequence of the Sorensen test the facilitator will apply current first aid techniques (rest, ice, compression, elevation).

There are no known harmful side-effects associated with temporary exposure to ultrasound scanners. Ultrasound waves can heat the tissues slightly. In some cases, it can also produce small pockets of gas in body fluids or tissues (cavitation).

Your confidentiality

Data collected will be de-identified for the purposes of publication or re-use for subsequent research projects. However, for the purpose of informing training program modifications identifiable data will be available for authorised support staff from your club. Please note:

- **“Identified” data means the identity of specific individual participants is known or can readily be ascertained.**
- **“De-identified” data means that all identifiers will be removed from the data prior to any publication of the data, re-use of the data (e.g. in related research) or sharing of the data (e.g. with other researchers). De-identified data can include information that has been coded so that it is possible to know that data relate to the same person, but it does not identify them.**

Your de-identified data collected will be presented in research publications and conferences in a way that will not reveal your identity nor allow you to be identified by third parties.

Your data will be securely stored in Dr Steven Duhig's office and only accessible, upon request, to the research team and authorised support staff of your team. Data is kept for five-years before deletion.

Your participation is voluntary

Your participation is voluntary and you are free to withdraw from the study at any time. Please know that should you wish to withdraw or decide not to participate then there will be no impact whatsoever to your relationship with the University.

Questions / further information

Should you wish for further information, please contact the Chief Investigator:

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The ethical conduct of this research

Griffith University conducts research in accordance with the *National Statement on Ethical Conduct in Human Research*. If potential participants have any concerns or complaints about the ethical conduct of the research project they should contact the Manager, Research Ethics on 3735 4375 or research-ethics@griffith.edu.au.

Feedback to you

Individual results from this study will be provided to each respective athlete and access to a plain language summary of overall research results via email request.

Privacy Statement – non disclosure

The conduct of this research involves the collection, access and/or use of your identified personal information. The information collected is confidential and will not be disclosed to third parties without your consent, except to meet government, legal or other regulatory authority requirements. A de-identified copy of this data may be used for other research purposes including publishing openly (e.g. in an open access repository). However, your anonymity will at all times be safeguarded. To ensure this happens with any images taken we will cover facial features. For further information consult the University's Privacy Plan at http://www.griffith.edu.au/about-griffith/plans-publications/griffith-university-privacy-plan or telephone (07) 3735 4375.

Appendix

Exploring the relationship between trunk extensor morphology and strength with lower back pain and leg injury risk in elite rugby league and Australian rules football players

CONSENT FORM

Research Team

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By signing below, I confirm that I have read and understood the information package and in particular:

- I understand that my involvement in this research will one session held at my team's training facility;
- I understand that my subsequent lower back pain and leg injury data will provided to the researchers at the end of the 2020 season
- I understand that the research may include photography/audio recording/audio-visual recording of my participation;
- I have had any questions answered to my satisfaction;
- I understand the risks involved;
- I understand that there will be no direct benefit to me from my participation in this research;
- I understand that my participation in this research is voluntary;
- I understand that if I have any additional questions I can contact the research team;
- I understand that I am free to withdraw at any time, without explanation or penalty;

- I understand that my name and other personal information that could identify me will be removed or de-identified in publications or presentations resulting from this research;

- I understand that I can contact the Manager, Research Ethics, at Griffith University Human Research Ethics Committee on 3735 4375 (or research.ethics@griffith.edu.au) if I have any concerns about the ethical conduct of the project; and

- I agree to participate in the project.

☐ I agree to participate in the project.

☐ I consent to the inclusion of my personal information in publications or presentations resulting from this research.

☐ I consent to the inclusion of my recorded voice or image in publications or presentations resulting from this research.

☐ I consent to the inclusion of my de-identified image in publications or presentations resulting from this research.

Name	
Signature	
Date	