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Original research

Hamstring and knee injuries are associated with isometric hip and trunk muscle strength in elite Australian Rules and Rugby League players

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ABSTRACT

Objectives: This study investigated relationships between isometric trunk and hip extensor strength, lumbar muscle morphology, and the risk of hamstring and knee ligament injuries in Australian Football League and National Rugby League players.

Design: Prospective cohort study.

Methods: Trunk and hip extensor strength, multifidus and quadratus lumborum cross-sectional area were measured during the 2020 pre-season. Logistic regressions and decision trees were employed to explore associations between maximum strength, strength endurance, multifidus and quadratus lumborum cross-sectional area, age, previous injuries, and hamstring and knee ligament injury risk.

Results: Greater strength endurance [odds ratio = 0.42 (0.23–0.74), $p = 0.004$] and maximum strength [odds ratio = 0.55 (0.31–0.94), $p = 0.039$] reduced hamstring injury risk. Increased risk of knee ligament injuries was associated with larger multifidus [odds ratio = 1.66 (1.14–2.45), $p = 0.008$] and higher multifidus to quadratus lumborum ratio (odds ratio = 1.57 (1.13–2.23), $p = 0.008$]. Decision tree models indicated that low strength endurance (< 99 Nm) characterised hamstring strains, while high (≥ 1.33) multifidus to quadratus lumborum ratio mitigated risk. Knee ligament injuries were associated with larger (≥ 8.49 cm2) multifidus, greater (≥ 1.25) multifidus to quadratus lumborum ratio, and lower maximum strength (< 9.24 N/kg).

Conclusions: Players with lower trunk and hip extensor maximum strength and strength endurance had increased risk of hamstring injuries, while knee ligament injury risk was elevated with larger multifidus cross-sectional area, higher multifidus to quadratus lumborum ratio, and lower maximum trunk and hip extensor strength.

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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 the estimation of hamstring strain injury risk.
- Lumbar morphology combined with trunk and hip extensor strength data is not able to improve knee ligament injury risk estimations.

1. 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[1,2] the incidence of non-contact lower limb injuries is similar[4–6] with hamstring strains and knee ligament injuries most prevalent.[7,8] Hamstring strains and knee ligament injuries presumably result from complex and potentially non-linear interactions between

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several modifiable and non-modifiable risk factors,[9–11] 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[12,13] with hamstring strength and strength-endurance,[10] hip abduction and external rotation strength, hip kinematics during running[14] and trunk proprioception[15] all being associated with greater propensity for hamstring strain or knee ligament injury.

Australian rules football players with smaller cross-sectional area (CSA) of the lumbar multifidus (LM) at the fifth lumbar vertebra (LM L5) and larger quadratus lumborum (QL) CSA have been shown to have an increased risk of any subsequent non-contact lower limb injuries.[16] Reduced contractile ability of the LM L5 during ultrasound imaging assessed via percentage change of muscle thickness during isometric contraction[17] and dominant, non-dominant side LM L5 asymmetry[18] were also suggested to be risk factors. Recently, we replicated these studies in both Australian Football League (AFL) and National Rugby League (NRL) players[9] finding AFL players who sustained non-contact lower limb injuries did indeed have larger QL CSA in preseason tests. However, trunk morphology measures of LM L5 CSA or LM L5 to QL ratio offered little insight into in-season non-contact lower limb injuries in either cohort. The LM and QL 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 CSA and pooled non-contact lower limb injuries. Whilst 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.[19] 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.[19] A multivariable approach aided by artificial intelligence methods can perform more complex injury risk assessments in team sports[20] and the addition of muscle function tests measuring trunk and hip extensor strength 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. The novel field test was based on a modification of the Biering-Sorensen test[21] 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 LM L5 CSA would be associated with a greater risk of subsequent non-contact hamstring strain and knee ligament injury.

2. Methods

2.1. Study design

This study is a continuation of our previously published work.[9] Professional players from two Australian Football League (AFL) and four National Rugby League (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 (AFL n = 87, NRL n = 151) underwent two-dimensional (2D) ultrasound imaging of their lumbar back muscles and 153 players (64 %, AFL n = 69, NRL n = 84) also agreed to participate in a novel assessment of isometric trunk and hip extensor strength using a modified Biering-Sorensen test.[21] 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 min 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.

2.2. Isometric trunk and hip extensor strength test

Players were asked to perform a modified version of the Biering-Sorensen test[21] 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 whilst wearing a custom-made harness that was anchored to the floor at the level of the xiphoid process (Fig. S1), thus ensuring an isometric contraction. A load cell (Vald Performance, Brisbane, Australia; sampling frequency: 100 Hz) 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 (minimal flexion/extension, see Fig. S1[22]) and horizontal (verified by investigators SD, MH) using a spirit level that was in contact with L5/S1 and C7 and players were instructed to cross their arms in front of their chest, limiting their contribution to force production. Due to time constraints encountered in elite sporting environments, there was no familiarisation session, however, the research team was informed that players were familiar with similar tests (e.g., Biering-Sorensen test). Players performed two sub-maximal warm-up repetitions (5/10 then 8/10 relative perceived exertion) followed by two maximal voluntary isometric contractions (MVICs) using the protocol of: 5 s MVIC, 5 s rest, followed by a 45 s MVIC.[23] A standardised instruction of ‘pull away from the ground as hard as possible’ was employed for all participants. Players were given visual feedback on their efforts by a real-time graph showing force production and verbal encouragement by the testing staff. Maximal efforts were deemed satisfactory when the force was higher than their second warm-up repetition and reached a distinct peak, and participants were asked to reattempt if lower. Our preliminary testing in recreationally active healthy adults has shown high test–retest reliability for both 5 s peak MVICs (intraclass correlation coefficient (ICC) = 0.89, coefficient of variation (CV) = 6.8 %) and 45 s mean MVICs (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 6 Hz lowpass filter with a stopband attenuation of 60 dB and compensation for filter delay in Matlab (The MathWorks, Natick, Massachusetts, USA). The filter cutoff frequency was chosen after pilot testing different cutoff frequencies on a set of five sample trials and demonstrated good results in removing unwanted high-frequency noise. Force produced by each participant was normalised based on body weight expressed as N/kg with maximum force produced during the 5 s MVICs (maximum strength) and mean force produced during the 45 s MVICs (strength endurance) used as the independent variables in the statistical analysis.

2.3. Ultrasound assessment

To achieve our secondary aim, we kept the data from the same trunk muscles investigated in previous work.[16,24] Ultrasound imaging data used in this investigation comes from the same dataset reported in our previously published study[9] (please refer to this article for detailed methodology). Ultrasound images of LM L5 and QL were obtained by two sonographers using B-mode ultrasound (LOGiQ-e, GE Healthcare, Milwaukee, WI) with a 5 MHz curvilinear transducer.[16,24] All imaging acquisition parameters were kept consistent (frequency: 5 MHz, gain: 60, depth: 8.0 cm) and tracing of all images was performed by one assessor.

2.4. Prospective injury definition

The main outcome of this study was non-contact hamstring and knee ligament injuries during the 2020 competitive AFL and NRL home and away seasons. The emphasis of this research centred around hamstring strains and knee ligament injuries, predicated on the suggested associations between muscular strength[10,11] and anatomical structure.[16,24] This focus was underscored by the fact that these specific injuries account for the majority of time lost in both the AFL and NRL. [5,25] Hamstring strain injuries were defined as acute injuries causing pain in posterior thigh regions, leading to missing at least one game. Each club's physiotherapy department clinically diagnosed damage to the hamstring muscle and/or tendon.[26] Knee ligament injuries include acute injuries to the anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), lateral collateral ligament (LCL) and medial collateral ligament (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.[3]

2.5. 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, body mass index (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 %,[27] data was imputed by a predictive mean matching approach[28] 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 0.2–0.5, and large 0.5–0.8.[29]

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, LM L5 CSA, QL CSA, previous non-contact lower limb injury with hamstring strain and knee ligament injury as the dichotomous dependent variable to calculate odds ratios (ORs) and 95 % confidence intervals (95 % CIs). For strength variables, ORs are expressed per one standard deviation in produced force. For all other variables ORs are expressed per one unit of measure. The 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: LM L5 CSA, QL CSA, LM to QL 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 node's contribution to the −2 log likelihood and log worth expressed as G^2 values. Receiver operator characteristic (ROC) curves were used to evaluate the predictive ability of the decision tree model. The ROC curve is a graphical plot that illustrates the diagnostic ability of a binary classifier system as its discrimination threshold is varied. It is created by plotting the true positive rate against the false positive rate at various threshold settings. The effectiveness of the model's predictions was quantified using the area under the curve (AUC) of the ROC plot. The AUC describes the ability of the model to discriminate between subsequently injured players and uninjured players, and is reported as excellent (0.90–1.00), good (0.80–0.90), fair (0.70–0.80), poor (0.60–0.70), or fail (0.50–0.60).[30] Due to the small sample size no data were held-back for validation.

3. Results

3.1. Player demographics and injury details

During the 2020 pre-season, 238 professional football players were assessed, and 153 players (age 23.2 ± 3.5 years, stature 187.2 ± 7.1 cm, mass 93.9 ± 11.7 kg, BMI 26.8 ± 2.9 kg/m^2, AFL n = 69 AFL, NRL n = 84) completed all testing with 126 (age 24.4 ± 3.8 years, stature 187.1 ± 6.4 cm, body mass 94.9 ± 11.5 kg, BMI 27.1 ± 2.8 kg/m^2, AFL n = 61 AFL, NRL n = 65) completing a prospective injury follow-up (see Fig. S2 for flow diagram, and Table 1 for player demographics). No significant differences in age, stature, body mass or BMI were found between players with a full injury follow-up and players lost to follow-up. Players lost to follow-up were significantly heavier (BMI, $p < 0.01$), whilst no differences were observed for other variables. Correlations between continuous variables are shown in Table S1 where two (body mass and BMI; QL CSA and LM L5 to QL ratio) correlations were above the a priori defined threshold (<0.7). A total of 84 (67 %) players who completed a 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 %).

3.2. Univariable logistic regression

Isometric trunk and hip extensor strength measures by injury group with univariable logistic regressions odds ratios are shown in Table 2. 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 LM L5 CSA (OR = 1.66 per 1 cm^2, 95 % CI = 1.14–2.45, p = 0.008, AUC = 0.65) and larger LM L5 to QL 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 1

Player demographics, LM L5 CSA, QL CSA, maximum trunk and hip extension strength and trunk and hip extension strength endurance by football code.

	AFL (n = 61)		NRL (n = 65)		p	d
	Mean	SD	Mean	SD		
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.

* Statistically significant ($p < 0.05$).

Table 2

Odds ratios (ORs), and significance values of univariable logistic regression based on age, previous non-contact lower limb injury, and isometric trunk and hip extensor strength parameters. ORs for age per one year and ORs for maximum strength and strength endurance are per one standard deviation.

	Hamstring strain injuries							Knee ligament injuries						
	Uninjured		Injured		Risk analysis			Uninjured		Injured		Risk analysis		
	Mean	SD	Mean	SD	ORs	95 % CIs	p	Mean	SD	Mean	SD	ORs	95 % CIs	p
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

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.

* Statistically significant ($p < 0.05$).

3.3. Decision tree model

Players who sustained a hamstring strain injury were characterised by low strength endurance (<3.42 N/kg). However, protection against hamstring strain injury was observed in players with higher strength endurance (≥ 3.42 N/kg) and those with lower strength endurance but high LM L5 to QL ratio (≥ 1.33). Players who sustained a knee ligament injury were characterised by larger LM L5 CSA (≥ 8.49 cm^2), larger LM L5 to QL ratios (≥ 1.25), and lower maximum strength (<9.24 N/kg) (Fig. 1). Protection from knee ligament injury was observed in smaller LM L5 CSA (<8.49 cm^2), or in those with a larger LM L5 CSA (≥ 9.48 cm^2) a low LM L5 to QL ratio (<1.25) and higher maximum strength (<9.24 N/kg) provided protection against knee ligament injuries. The decision tree representing hamstring strain injuries pooled across AFL and NRL provided acceptable ROC (AUC = 0.75) whilst assessing pooled knee ligament injuries showed an excellent discriminatory effect (AUC = 0.82).

4. 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 LM L5 CSA, greater LM L5 to QL ratio, and lower maximum strength was characteristic 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 in a cohort of AFL and NRL players. Hamstring strain injuries occur via two mechanisms, each involving different aspects of muscle-tendon unit dynamics: active contraction elements and passive tensile elements. Most running induced injuries are thought to occur during the terminal-swing phase of high-speed running, where the muscle actively lengthens to decelerate the forward swinging shank. This mechanism involves active elements of the muscle, with factors such as unaccustomed high-speed running loads,[26] low eccentric knee flexor strength, and limited knee flexor strength endurance,[14,31] suggested to increase the risk of hamstring strain injury. Stretch-induced hamstring strain injuries are caused by high stress and strain, seen during hip flexion with an extended knee (e.g., kicking a ball).[32] The passive tensile strength of the muscle-tendon unit is critical in withstanding the applied stretch.[32] 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. Moreover, the trunk's ability to resist hip flexion could potentially reduce the risk of sustaining a stretch-induced hamstring strain. For example, surface EMG patterns during maximal acceleration showed that amateur soccer players with higher activity of trunk and gluteal muscles during running were at lower risk of sustaining a subsequent hamstring strain injury suggesting that intermuscular co-ordination was a relevant parameter when assessing hamstring strain injury risk.[31] A prospective follow-up study[14] 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. 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.[33] It might therefore be argued that intramuscular coordination makes a significant contribution to hamstring fatigue and injury risk.[31]

Knee ligament injuries demonstrated a significant association with lumbar morphological variables. Knee ligament injury risk increased with larger LM L5 and LM L5 to QL ratio. From the decision tree model the combination of larger LM L5 CSA, greater LM L5 to QL ratio, and lower maximum strength was characteristic of those who sustained a knee ligament injury. We rejected our hypothesis of smaller LM L5 CSA being a risk factor for non-contact knee ligament injuries, which may be explained partly by our cohort's different demographics to prior research. A potential explanation for the association between a larger LM L5 CSA and LM L5 to QL ratio and increased knee ligament risk could be linked to the correlation between LM L5 CSA and BMI (Table S1), which is consistent with previous work suggesting an elevated risk of knee ligament injury with increased BMI.[34] Additionally, from a morphological standpoint, a larger LM L5 CSA and LM L5 to QL ratio might represent a higher muscle volume and potentially an enhanced maximal strength capacity. Contrarily, our study found that players with lower strength had a higher risk of knee ligament injury. This seeming paradox might be attributed to potential imbalances in the kinetic chain, where despite larger muscle size, the actual strength might be insufficient, or the coordination between different muscle groups could be compromised. The resultant suboptimal movement patterns and biomechanics could thus expose the knee ligaments to excessive strain during high-intensity activities, thereby elevating injury risk.[34] Pooling data across both cohorts for knee ligament injuries potentially caused a skewing effect since NRL players were significantly heavier and had higher BMI than AFL players. Investigating whether the AFL and NRL cohorts show different associations with knee ligament injuries due to different body mass can be relevant for future research but was not possible in this study due to insufficient sample sizes. Similarly, an investigation exploring the effect playing positions (forwards vs backs) have on risk profiles would also require a larger sample size. It must be noted that the receiver operator characteristics for our knee

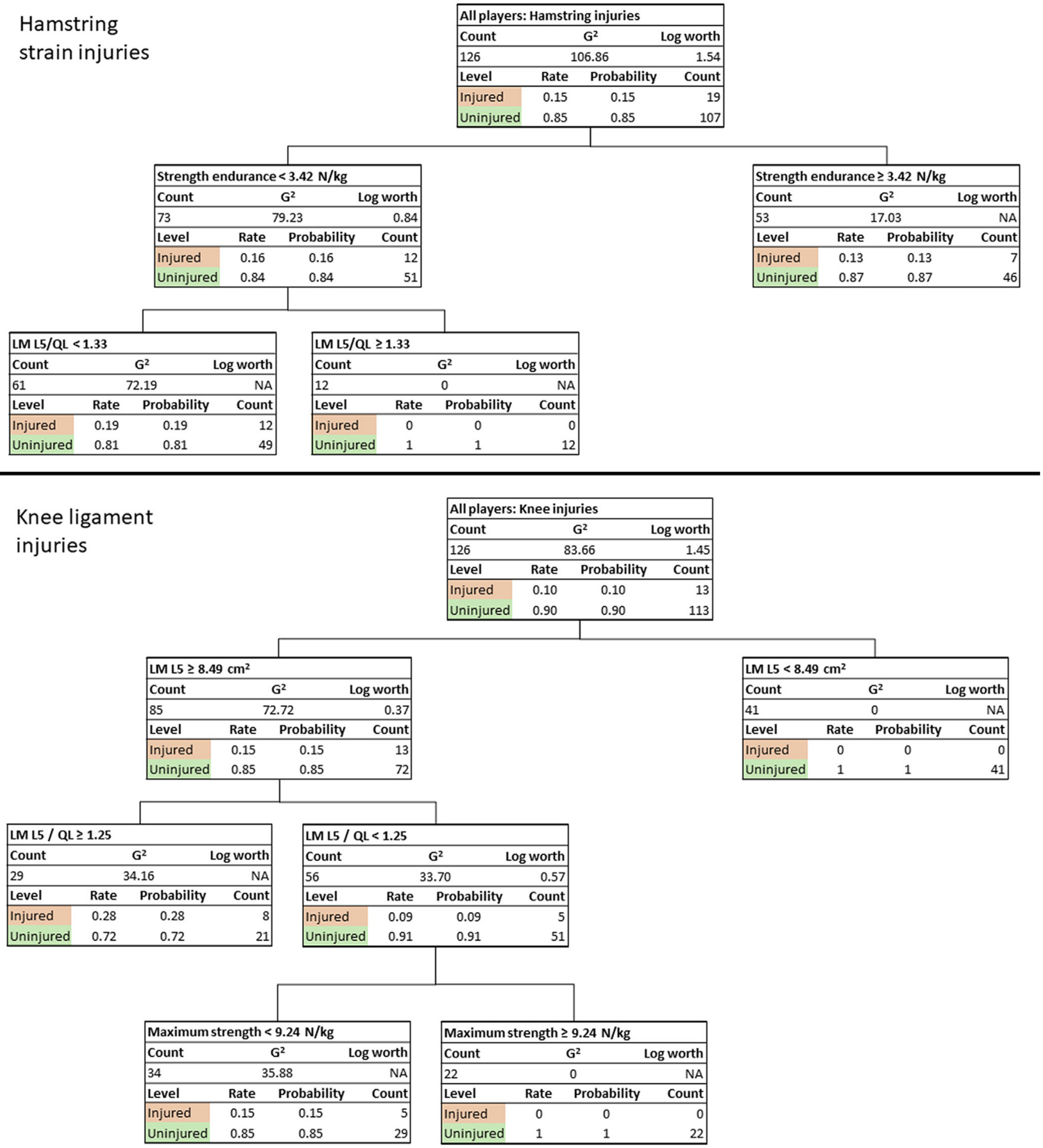

Fig. 1. Decision tree plot visualising multivariable contributions to knee and hamstring injury risk. Top tree represents hamstring injuries, bottom tree represents knee injuries. $G^2 = G^2$ statistics indicating contribution to −2 log likelihood of each node, LM L5 = lumbar multifidus at 5th lumbar vertebrae, QL = quadratus lumborum, CSA = cross-sectional area.

ligament injury models do 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 players from two different competitions (AFL and NRL) that have similar prevalence of hamstring strain and knee ligament injuries.[5,25] 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 LM L5 to QL 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.

4.1. 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.

The novel and high-intensity nature of the trunk and hip extensor strength test led to some uncertainty, resulting in 85 players declining to participate. This loss limits the generalisability of our findings. Moreover, we acknowledge the potential bias this might have introduced, with the possibility that those with weak or sensitive trunks, a cohort of interest, might have been disproportionately represented among the non-participants. Notably, there were no adverse events reported during or after strength assessments. This incident-free record provides a substantial basis for reassuring players and support staff regarding the safety and acceptability of this testing methodology in future investigations.

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.[35] 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.

5. Conclusion

This study was the first to identify associations between lower isometric trunk and hip extensor strength and increased hamstring strain injury risk in AFL and NRL players. Increased LM L5 CSA 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 programmes for both football codes.

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Confirmation of ethical compliance

All players provided written informed consent prior to participating, which was approved by the Griffith University Human Ethics Committee (GU Ref No: 2019/106).

CRediT authorship contribution statement

Martin Hajek: Data collection, Data analysis, Conceptualisation, Writing - original draft preparation. **Morgan Williams:** Data analysis, Writing -reviewing and editing. **Matthew Bourne:** Conceptualisation, Writing - reviewing and editing, Supervision. **Llion Roberts:** Conceptualisation, Writing - reviewing and editing, Supervision. **Norman Morris:** Supervision. **Anthony Shield:** Conceptualisation, Writing - reviewing and editing. **Jonathon Headrick:** Conceptualisation, Writing - reviewing and editing. **Steven Duhig:** Data collection, Supervision, Conceptualisation, Writing - reviewing and editing.

Declaration of interest statement

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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