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RUNNING TITLE

Eccentric hamstring strength and injury risk.

CONFLICT OF INTEREST

NA

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ABSTRACT

Purpose: Is eccentric hamstring strength and between limb imbalance in eccentric strength, measured during the Nordic hamstring exercise, a risk factor for hamstring strain injury (HSI)? **Methods:** Elite Australian footballers (n=210) from five different teams participated. Eccentric hamstring strength during the Nordic was taken at the commencement and conclusion of preseason training and in season. Injury history and demographic data were also collected. Reports on prospectively occurring HSIs were completed by team medical staff. Relative risk (RR) was determined for univariate data and logistic regression was employed for multivariate data. **Results:** Twenty-eight HSIs were recorded. Eccentric hamstring strength below 256N at the start of preseason and 279N at the end of preseason increased risk of future HSI 2.7 (relative risk, 2.7; 95% confidence interval, 1.3 to 5.5; p = 0.006) and 4.3 fold (relative risk, 4.3; 95% confidence interval, 1.7 to 11.0; p = 0.002) respectively. Between limb imbalance in strength of greater than 10% did not increase the risk of future HSI. Univariate analysis did not reveal a significantly greater relative risk for future HSI in athletes who had sustained a lower limb injury of any kind within the last 12 months. Logistic regression revealed interactions between both athlete age and history of HSI with eccentric hamstring strength, whereby the likelihood of future HSI in older athletes or athletes with a history of HSI was reduced if an athlete had high levels of eccentric strength. **Conclusion:** Low levels of eccentric hamstring strength increased the risk of future HSI. Interaction effects suggest that the additional risk of future HSI associated with advancing age or previous injury was mitigated by higher levels of eccentric hamstring strength. **KEY WORDS**: Nordic hamstring exercise, prospective, muscle injury, epidemiology.

INTRODUCTION

Australian football is a dynamic game which shares characteristics with soccer (high aerobic running demands), rugby (upper limb tackling) and Gaelic football (punting kicking), whilst being unique with regards to a large field size and high number of player interchanges allowed.(20) Like many other sports,(5, 15, 25) Australian football imposes a risk of injury to its participants.(20) Hamstring strain injury (HSI) has been the predominate cause of lost playing time at the elite level of Australian football for more than 20 years(20) and results in significant financial loss to teams via athlete unavailability.(12) A number of non-modifiable risk factors for HSIs in Australian footballers have been identified previously, most prominently increasing age and previous injury.(10, 19, 24) However, in recent times, a greater emphasis has been placed on modifiable risk factors,(2) which have the scope to be altered with appropriate interventions and can lead to reductions in an athlete's risk of injury.(2) Of these modifiable risk factors, eccentric hamstring strength and between limb imbalances in strength have received the most attention,(6, 22, 26) however, the role of hamstring strength in the aetiology of HSIs in elite Australian football remains controversial.(3, 14, 18) Whilst eccentric strength, between limb strength imbalance and hamstring to quadriceps ratios have shown an association with the future incidence of HSI in professional soccer(6) and sub-elite sprinters,(22) a recent meta-analysis found that isokinetically-derived eccentric hamstring strength was not a risk factor for future injury.(8) In prospective studies which examine eccentric hamstring strength and strength ratios as a risk factor for future HSI, isokinetic dynamometry has been the chosen strength testing methodology.(3, 6, 22, 26) Whilst isokinetic dynamometry is considered the gold standard tool for assessing eccentric hamstring strength, its wide spread application is limited due to the device being largely inaccessible and expensive to purchase(16) and its use as a predictor of future HSI risk is questionable.(9) Further to this, the time taken to complete an assessment of an individual athlete (up to 20 minutes), normally at an off-site location, is prohibitive in elite sporting environments.(16)

We have recently developed a novel field testing device for the assessment of eccentric hamstring strength to overcome the limitations of isokinetic dynamometry.(16) Using the commonly employed Nordic hamstring exercise, the device is able to record maximal eccentric hamstring strength and between limb imbalances, with an assessment time of less than two minutes per athlete. Whilst this device is a reliable measure of eccentric knee flexor forces during the Nordic hamstring exercise,(16) there is currently no literature examining whether measures derived from this device are predictive of an athlete's risk of future HSI. The Nordic hamstring exercise is the best supported exercise in the literature for the prevention of HSI(1, 21) and it might reasonably be expected that the measurement of eccentric hamstring strength during this exercise could provide some information as to the risk of future HSI. Recently it has also been suggested that the interaction between previously identified non-modifiable risk factors, such as increasing age and previous history of injury, and modifiable factors, such as strength needs to be considered.(23) A greater understanding of how various risk factors interact with one another is likely to give practitioners a better understanding of an athlete's risk of injury compared to univariate or independent risk factors.

The purpose of this study was to determine if eccentric hamstring strength and between limb imbalances in eccentric hamstring strength, derived from the aforementioned field testing device was predictive of future HSI risk in elite Australian footballers across the pre-season and in-season periods. Furthermore, the study also aimed to examine the interrelationship between previously identified risk factors, namely increasing age and previous HSI, and eccentric hamstring strength, when determining risk of future HSI. The primary hypothesis was that the athletes who sustained a HSI would display lower levels of eccentric hamstring strength and larger between limb imbalances in eccentric hamstring strength compared to their uninjured counterparts. In addition we explored the interaction between increasing age, previous HSI and eccentric strength and how these factors combined influence the probability of future HSI.

METHODS

Participants & study design

This prospective cohort study was approved by the Queensland University of Technology Human Research Ethics Committee and was completed during the 2013 Australian Football League season, during the pre- (November 2012 to February 2013) and in-season (March 2013 to September 2013) periods. Five of the six professional teams invited to participate elected to take part in the study. All members of the playing squad for each team (approximately 42-45 athletes per team) were approached and provided with a plain language statement explaining the study. In total, 210 elite male Australian footballers gave informed written consent to participate. Prior to the commencement of data collection, team medical staff completed a previous injury questionnaire which detailed, for all athletes, the history of hamstring, quadriceps and calf strain injuries and chronic groin pain within the preceding 12 months and the history of anterior cruciate ligament (ACL) injury at any stage in the athlete's career. These previous injury reports were completed with information from each club's internal medical recording system. Athletes had their eccentric hamstring strength assessed at three time points throughout the season; start of preseason training (November 2012), end of preseason training (February 2013) and during the middle of the competitive season (June/July 2013). All players deemed fit by team medical staff to complete testing at each time point were assessed. For athletes who suffered a HSI during the study period a standard hamstring injury report form was completed by club medical staff. At the conclusion of the season, club staff also reported on each athlete's primary position on the field. If athletes played multiple positions the club was asked to identify a single position which was most representative of the athletes match play demands. As per previous work (4) these playing positions were defined as: centre-half back, centre-half forward, full back, full forward, small back, small forward, midfielder and ruckman.

Eccentric hamstring strength assessment

The assessment of eccentric hamstring strength using the Nordic hamstring exercise field testing device has been reported previously.(16) Participants knelt on a padded board, with the ankles secured immediately superior to the lateral malleolus by individual ankle braces which were attached to custom made uniaxial load cells (Delphi Force Measurement, Gold Coast, Australia) with wireless data acquisition capabilities (Mantracourt, Devon, UK). The ankle braces and load cells were secured to a pivot which allowed the force to always be measured through the long axis of the load cells. Following a warm up set, participants performed one set of three maximal repetitions of the bilateral Nordic hamstring exercises. Instructions to players were to gradually lean forward at the slowest possible speed while maximally resisting this movement with both limbs while keeping the trunk and hips held in a neutral position throughout, and the hands held across the chest.(16) Participants were loudly exhorted to provide maximal effort throughout each repetition. A trial was deemed acceptable when the force output reached a distinct peak (indicative of maximal eccentric strength), followed by a rapid decline in force which occurred when the athlete was no longer able to resist the effects of gravity acting on the segment above the knee joint.

Prospective hamstring strain injury reporting

For the purposes of this study, a HSI was defined as acute pain in the posterior thigh which caused immediate cessation of exercise and damage to the muscle and or tendon which was later confirmed with MRI examination. Reports were not completed for injuries which did not fulfil these criteria. For all HSIs which fit these inclusion criteria in the study period, the team doctor or physiotherapist completed a standard injury report form which detailed which limb was injured (dominant/non dominant limb, left / right), the muscle injured (biceps femoris long head/biceps femoris short head/semimembranosus/semitendinosus), location of injury (proximal/distal, muscle belly/muscle-tendon junction), activity type performed at time of injury (ie, running, kicking), grade of injury (I, II, or III) and the number of days taken to return to full participation in training/competition. At the conclusion of the competitive season these reports were forwarded to the investigators.

Data analysis

Eccentric hamstring force data for each limb were transferred to a personal computer at 100 Hz through a wireless USB base station receiver (Mantracourt, Devon, UK). Subsequently, the peak force for the three repetitions for each limbs (left and right) was determined using LabChart 7.3 (ADInstruments, New South Wales, Australia). Eccentric hamstring strength, reported in absolute terms (N) and relative to body mass ($N.kg^{-1}$), was determined as the average of the peak forces from the 3 repetitions for each limbs, resulting in a left and right limb measure of eccentric strength.(16)

The between limb imbalance in eccentric hamstring force was calculated as a left:right limb ratio for the uninjured group and as an uninjured:injured limb ratio in the injured group.

The between limb imbalance ratio was converted to percentage difference as recommended(13) using log transformed raw data followed by back transformation. Negative percentage imbalances indicate that the left limb was stronger than the right limb in the uninjured group or that the injured limb was stronger than the uninjured limb in the injured group. For athletes who remained free of HSI, the eccentric hamstring strength measurements from the left and right limbs were averaged, as the limbs did not differ ($p > 0.05$), to give a single control group strength score. If an athlete sustained a HSI their eccentric hamstring strength was not considered at future time points.

Statistical analysis

All statistical analysis was performed using JMP 10.02 (SAS Institute, Inc). Mean and standard deviations (SD) of age, height and body mass at the start of the study and eccentric hamstring strength and strength imbalance at all three time points were determined. Univariate analysis was performed to compare age, height, weight, percentage between limb imbalance between the injured and uninjured groups, eccentric hamstring strength of the injured limb, the contralateral uninjured limb and the average of the left and right limbs from the uninjured group using Students t test at all three time points, with Bonferonni corrections performed to account for multiple comparisons. To determine univariate relative risk (RR) and 95% confidence intervals (95%CI) of future HSI, athletes were grouped according to

- with or without prior
    - hamstring,
    - calf,

- quadriceps,
- ACL,
- groin injury

- average eccentric knee flexor strength thresholds above or below
  - 256N at the start of preseason
  - 279N at the end of preseason
    - Which were determined using receiver operator characteristic curves based on the strength threshold that maximised the difference between sensitivity and 1 - specificity
- limbs above or below a 10%, 15% & 20% between limb strength imbalance
  - at the start of preseason
  - end of preseason
- athletes above age cut off's
  - 18.9 years
  - 20.1 years
  - 22.6 years
  - 25.5 years
  - 28.9 years

- athletes between height and weight cut offs defined previously by Gabbe and colleagues.(10)

HSI rates from these groups were then compared and RR determined and significance assessed via a two-tailed Fisher's exact test. In addition, univariate logistic regression was conducted with prospective HSI occurrence as a dichotomous dependent variable and average eccentric knee flexor strength at the start and end of preseason as continuous independent variables in separate analyses. These data are reported as odds ratios (OR) and 95% confidence intervals (95%CI) per 10N increment in force.

To improve the understanding of risk from the univariate analysis and remove possible confounding effects two multivariate logistic regression models were built using risk factors identified in previously published evidence(10, 19, 24) and the findings from the current research. The first model included mean (average of both limbs) eccentric strength from the start of preseason and history of HSI and their interaction. The mean eccentric strength of both limbs was used following data screening that showed that right leg eccentric peak force was highly related ($r = 0.75$) to the left leg peak force. The second model again included mean (average of both limbs) eccentric strength from the start of preseason but this time included the participant's age. Although a third model including both age and history of HSI was built, it was not reported since it confirmed previous work that suggested age is a confounder to history of HSI with regards to predicting injury risk since those who are older are more likely to have a history of HSI. Significance was set at $p < 0.05$ for all analyses and where appropriate Cohen's *d* was used to calculate effect size. For univariate analysis, the difference between limbs/groups is expressed as mean differences and 95%CI.

RESULTS

Post hoc power calculations

Using eccentric strength data from the start of preseason testing time point power was calculated as 0.97 for the use of two-tailed independent t test to compare groups (input parameters, effect size = 0.80; alpha = 0.05, sample size group 1 = 182, sample size group 2 = 27) using G*Power (version 3.1.7).

Cohort and prospective injury details

Two-hundred and ten athletes (age, 23.3 ± 3.7 years; height, 188.0 ± 7.2 cm; mass, 87.3 ± 8.2 kg) were assessed on at least one occasion; of which 121 were assessed at all three time points, 156 were assessed at the start and end of pre-season and 186 were assessed at the start of preseason. From the total sample of 210, 182 athletes did not sustain a HSI (age, 23.2 ± 3.7 years; height, 188.4 ± 7.2 cm; mass, 87.9 ± 7.9 kg) and 28 did (age, 23.9 ± 3.6 years; height, 185.1 ± 6.2 cm; mass, 84.3 ± 5.6 kg). The athletes that went on to be injured displayed lesser height and mass compared to the uninjured athletes ($p < 0.05$). Twenty-eight HSIs were sustained (19 left limb, 9 right limb) and of these six injuries reoccurred within the study period. Of the 28 initial HSIs 78.6% were in the biceps femoris long head, 17.9% in the semimembranosus and 3.6% in the semitendinosus. High speed running was the primary mechanism of injury (60.7%) followed by kicking (17.9%) and running whilst bent over to collect the ball (7.1%). No injuries were sustained during the Nordic hamstring exercise testing sessions. Of the 28 initial HSIs, five occurred in pre-season (between start of pre-season and end of pre-season strength assessments), 16 occurred during the early part of in-season (between end of pre-season and mid-season strength assessments) and seven occurred during the late in-season period (after the mid-season strength assessment). The number of athletes which had their eccentric knee flexor strength assessed at each time point was: start of preseason, 186 (27 went on to sustain HSIs); end of preseason, 184 (17 went on to sustain HSIs); in season, 155 (2 went on to sustain HSIs). The distribution of player positions in the subsequently injured group (centre-half back, 4%; centre-half forward, 4%; full back, 4%; full forward, 4%; small back, 18%; small forward, 29%; midfielder, 36%; ruckman, 4%) compared to the uninjured group (centre-half back, 12%; centre-half forward, 6%; full back, 7%; full forward, 5%; small back, 18%; small forward, 14%; midfielder, 31%; ruckman, 8%) suggested that centre-half backs and ruckmen were under-represented in the subsequently injured group whereas small forwards were over-represented.

Univariate analysis

Eccentric hamstring strength and between limb imbalances at all three time points for the subsequently injured and uninjured limbs from the injured group and the average of both limbs from the uninjured group can be found in Table 1. Using absolute strength measures, the subsequently injured limbs were significantly weaker at the start (mean difference, 55N; 95%CI, 21 to 89 N; $p = 0.002$;$d = 0.67$) and end of pre-season (mean difference, 46N; 95%CI, 9 to 83 N; $p = 0.014$;$d = 0.61$) compared to the average of both limbs in the uninjured group. There were no significant differences ($p>0.05$) in absolute eccentric hamstring strength between the injured limb and contralateral uninjured limb at any time point. Eccentric strength from the uninjured limb from the injured group did not differ from the average of both limbs from the uninjured group at the start of preseason ($p = 0.108$) but it was lower at the end of preseason (mean difference, 39N; 95%CI, 2 to 75N; $p = 0.038$, $d = 0.53$). Eccentric hamstring strength relative to body mass showed similar differences, with the subsequently injured limb weaker than the average of both limbs in the control group at the start (mean difference, 0.77 $N.kg^{-1}$; 95%CI, 0.34 to 1.20$N.kg^{-1}$; p = 0.001 ; *d* = 0.76) and end (mean difference, 0.68$N.kg^{-1}$; 95%CI, 0.21 to 1.14$N.kg^{-1}$; p = 0.005; *d* = 0.73) of preseason. Similarly the uninjured limb from the injured group was weaker than the average of both limbs in the control group at the start (mean difference, 0.45$N.kg^{-1}$; 95%CI, 0.01 to 0.88$N.kg^{-1}$; p =0.046; *d* = 0.36) and end (mean difference, 0.58$N.kg^{-1}$; 95%CI, 0.12 to 1.04$N.kg^{-1}$; p = 0.014; *d* = 0.66) of preseason. Between limb imbalance in eccentric hamstring strength did not differ between the subsequently injured and uninjured groups at the start of preseason (mean difference, -3.0%; 95%CI, -11.7 to 5.7%; p = 0.498; *d* = -0.13) or the end of preseason (mean difference, -2.6%; 95%CI, -7.6 to 2.4%; p = 0.306; *d* = -0.27). There was no difference between the age of the subsequently injured and uninjured athletes (mean difference, -0.7 years; 95%CI, -2.2 to 0.8 years; p = 0.250; *d* = -0.19), however height (mean difference, 3.3 cm; 95%CI, 0.5 to 6.1 cm; p = 0.024; *d* = 0.49) and weight (mean difference, 3.6 kg; 95%CI, 0.5 to 6.7 kg; p = 0.021; *d* = 0.53) were significantly higher in the uninjured group. Average absolute eccentric knee flexor strength at the start (OR = 0.937; 95%CI, 0.888 to 0.990; p = 0.020) and end (OR = 0.914; 95%CI, 0.845 to 0.989; p = 0.026) of pre-season, using univariate logistic regression, was found to have a significant inverse relationship with the incidence of prospectively occurring HSIs. As such, for every 10N increases in eccentric knee flexor strength the risk of HSI was reduced by 6.3% (early preseason) and 8.9% (late preseason) respectively.

Relative risk

The impact of prior HSI, ACL injury, calf, quadriceps and chronic groin pain on the RR of future HSI can be found in Table 2. Athletes with average limb strength below the receiver-operator-curve determined thresholds of 256N (Area under the curve = 0.65; sensitivity = 0.63; 1

– specificity = 0.35) at the start of preseason and 279N (Area under the curve = 0.67; sensitivity = 0.65; 1 – specificity = 0.26) at the end of preseason had 2.7 (RR, 2.7; 95%CI, 1.3 to 5.5; p = 0.006) and 4.3 (RR, 4.3; 95%CI, 1.7 to 11.0; p = 0.002) times greater risk of subsequent HSI, respectively. Similar RR were seen for eccentric strength normalised to body mass, however no measure of between limb imbalance lead to a statistically significant increase in RR (Table 2)

Multivariate logistic regression

Details of both logistic regression models can be found in Table 3, Figure 1 & 2. While models were significant (model 1, previous HSI & eccentric strength at the start of preseason, p = 0.021; model 2, age & eccentric strength at the start of preseason, p = 0.009) only the interaction of age and eccentric strength reached significance (p = 0.025). The interaction between previous HSI and eccentric strength was not significant (p = 0.406). For both models it was eccentric strength at the start of preseason which made a significant contribution to the model.

DISCUSSION

The purpose of this study was to determine if elite Australian footballers with lower levels of eccentric hamstring strength and larger between limb strength imbalances were at an elevated risk of future HSI. The key unique findings from this study were that: 1) limbs that went on to sustain a HSI were significantly weaker than the limbs of uninjured athletes at the start and end of preseason, 2) between limb imbalance in eccentric hamstring strength did not differ between the uninjured or injured groups nor did an imbalance of 10, 15 or 20% increase the risk of future HSI and 3) the interaction of age and history of HSI with eccentric strength provided additional information on athlete risk profile, compared to age and history of HSI alone.

Lower levels of eccentric hamstring strength, and not between limb imbalance, assessed during the Nordic hamstring exercise, increased the risk of subsequent HSI in elite Australian footballers. Given that close to two-thirds of the HSIs reported in the current study occurred during high-speed running, low levels of eccentric strength might suggest a reduced ability of the hamstrings to decelerate the forward moving leg during the terminal swing phase of gait(17) which may lead to an acute injury, although when in the gait cycle the hamstrings are most susceptible to strain injury remains controversial. The relationship seen in the present study between eccentric hamstring weakness and HSI differs from the one other major study examining eccentric strength and HSI risk in Australian football.(3) However, this previous study looked at isokinetic strength measures in a smaller sample (*n* =102) with a mixture of elite and non-elite athletes and this may account for the divergent findings. The different testing methodologies is the most likely explanation of the disparate findings between the current study and the work from Bennell and colleagues(3). Firstly, the Nordic hamstring test is bilateral, compared to the isokinetic testing which involves unilateral strength assessments. Secondly, the external torque around the knee joint, that an athlete is required to resist via forceful knee flexor contraction during the Nordic hamstring exercise, increases as the athlete progresses towards the ground, whereas isokinetic testing involves maximal effort throughout the entire range of motion. The increasing demands of the Nordic hamstring exercise throughout the range of motion might indicate that stronger individuals are also able to progress further through the exercise and this might also be a surrogate indicator of more strength at longer muscle length.

Contrary to the hypothesis and a previous findings in elite soccer,(7) between limb imbalances in eccentric strength of 10, 15 and 20% did not increase the risk of HSI. This finding corroborates previous work in Australian football(3) and recent findings in American football using concentric isokinetic measures,(27) which have found no relationship between incidence of HSI and between limb knee flexor strength imbalance. It may be that excessively large between limb imbalance (perhaps >25%) increases the risk of injury (particularly given the typical error as a percentage of co-efficient of variation reported for left-to-right limb imbalance measure using the Nordic testing device is 6.0%)(16) however a study with a larger sample size would be required to explore this further. It should also be acknowledged that the test of between limb imbalance in this study, the Nordic hamstring exercise, was bilateral in nature. Other tests of imbalance typically involve unilateral maximal efforts (7, 3, 27) and as such the results are not directly comparable. We chose to employ the traditional bilateral Nordic hamstring exercise because we have previously shown that ait has greater reliability (intraclass correlation coefficient = 0.85) than a unilateral Nordic test (intraclass correlation coefficient = 0.55).(16) Further work is required on the validity of a bilateral test as a measure of between limb imbalance.

The examination of the interaction between eccentric strength at the start of preseason with age and previous HSI, respectively, also provides novel information on risk profiles for HSIs in elite Australian footballers. Age and previous HSI have both been identified as independent risk factors for future HSI in Australian football.(10, 19, 24) The current data (Figure 1 & 2) indicates that the elevated probability of HSI in older athletes or those with a previous HSI can be offset by higher levels of eccentric hamstring strength. In light of these findings it should be considered that increasing age and previous HSI only elevate the likelihood of injury if the athlete also has relatively low levels of eccentric hamstring strength. Such evidence, if replicated in future studies, might cause a shift in the understanding of risk factor analysis for injury. The idea that non-modifiable risk of future injury can be modulated via alterations in modifiable factors is worthy of further exploration for HSIs in other sports and pathologies. Indeed, risk of recurrent HSI has been significantly reduced following eccentric strength intervention(21) suggesting that, in this case, the term non-modifiable risk factor is a misnomer.

Despite the lack of difference in age and injury history variables between the injured and uninjured groups, logistic regression revealed a significant interrelationship between age, previous HSI (non-modifiable risk factors) and eccentric hamstring strength (modifiable risk factor). Most notably, older players who display lower levels of eccentric hamstring strength at the start of preseason were far more likely to sustain a HSI compared to younger players with the same level of strength. As an example, a 33-year old with eccentric hamstring strength of 159 N at the start of preseason has a 78% chance of sustaining a future HSI, compared to a 20% chance of a HSI for a 22-year old with the same level of strength. It may be tempting to suggest that the differences in height and weight noted between the uninjured and uninjured groups could confound measures of eccentric hamstring strength, given the load experience around the knee joint during the Nordic hamstring exercise is influenced by height and weight.(16) However, correlation analysis revealed r^2 values of 0.02 (height vs strength) and 0.04 (weight vs strength), suggesting that these anthropometric variables do not impact upon eccentric strength measures using the device from the present study. This was further confirmed by the use of eccentric knee flexor strength normalised to body mass, which was also lower in the injured compared to uninjured athletes. Examination of the distribution of player position data did identify that small forwards were over-represented in the subsequently injured group when compared to the uninjured group, whereas centre-half backs and ruckmen where under-represented. This distribution may have influenced the anthropometric characteristics of the groups, as small forwards were on average 181.5cm tall and weighed 82.1kg, which is shorter and lighter than the cohort average. Why these specific positional players were over-represented in the subsequently injured group remains to be seen, however it should be noted that in Australian football, small forwards often play hybrid roles in both the forward line and the midfield and these extensive running demands and this exposure may impose additional risk. It is likely that the under-representation of centre-half backs and ruckmen is due to lesser running demands of these positions.(4) Given the complex nature of Australian football, with unlimited substitutions (although this rule changed in the following season) and with athletes asked to play multiple positions, simple data on primary athlete position is most likely not sufficient to elucidate the relationship between player role in game and HSI risk.

We acknowledge some limitations in this study. Firstly, the lack of exposure data does not allow for the determination of injury incidence between groups relative to time of exposure. Future work should examine total exposure and exposure to high speed running to examine the influence of this on injury risk. Secondly, the study was performed only on elite Australian footballers and generalising these findings to other athletic groups should be done with caution. Similar studies examining athletes from other sports are warranted to determine if the same relationship exists in a wider population. Thirdly, the eccentric strength measures were measured as a force output and not converted to a joint torque. Athletes with a longer lower leg lever (distance from knee joint axis of rotation to the ankle strap) would produce more torque than athletes with a comparatively smaller lever, despite the same force output. Despite this, the force measure still provided useful information as to an athlete's risk of HSI. Whether a torque measure would be a more sensitive measure remains to be seen. Finally, the knee flexor measures were not made relative to an anterior muscle group such as the knee extensors or the hip flexors, which might have allowed for the determination of a hamstring to quadriceps ratio, or something similar. It might be argued that an index of knee flexor to knee extensor(6) or hip flexor(26) strength might increase the specificity and/or sensitivity of the measures derived from the current strength assessment. Despite this, the eccentric strength measures taken at the start and end of preseason provided information as to the risk of future injury and this information is valuable for practitioners looking to minimise the risk of HSI.

In conclusion, elite Australian footballers, who displayed low levels of eccentric hamstring strength during the Nordic hamstring exercise when assessed at the start and end of preseason displayed significantly greater risk of future HSI compared to stronger athletes. However, a larger between limb imbalance in eccentric strength of the hamstrings did not significantly increase the risk of HSI. The interrelationship between eccentric hamstring strength and previously identified risk factors for HSI should assist in better assessing an individual's risk of future injury.

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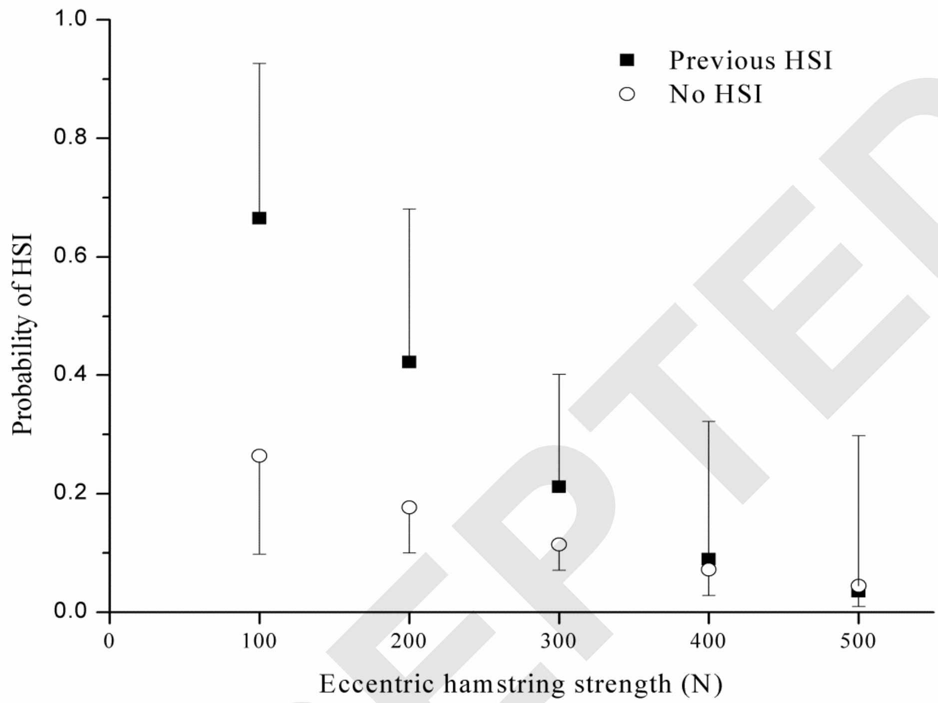
FIGURE CAPTIONS

Figure 1. The non-significant interaction between eccentric hamstring strength at the start of preseason training, history of hamstring strain injury (HSI) and probability of future HSI (error bars indicate 95% confidence intervals).

Figure 2. The interaction between eccentric hamstring strength at the start of preseason training, age and probability of future hamstring strain injury (HSI). The ages are representative of the 10^{th}, 25^{th}, 50^{th}, 75^{th} and 90^{th} percentile of the cohort. The additional likelihood of future HSI in older athletes is pronounced at low levels of eccentric hamstring strength, however this risk can be offset with increasing eccentric hamstring strength. Note that data has been offset (to the left or right) on the x axis to allow for the visibility of error bars for all age groups. The data points and error bars are reflective of data at 100, 200, 300, 400 and 500N for all groups.

Figure 1



Previous HSI
No HSI
Probability of HSI
0.0
0.2
0.4
0.6
0.8
1.0
0
100
200
300
400
500
Eccentric hamstring strength (N)

Figure 2

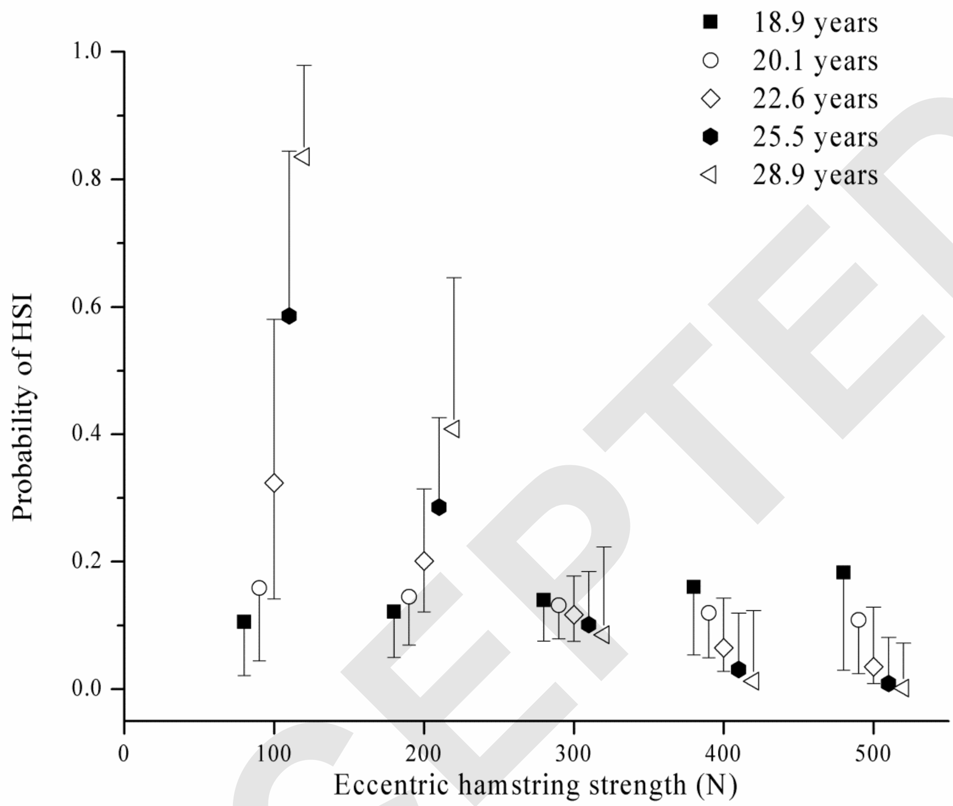

18.9 years
20.1 years
22.6 years
25.5 years
28.9 years
Probability of HSI
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
Eccentric hamstring strength (N)

Table 1. Nordic hamstring exercise force variables from hamstring strain injured and uninjured elite Australian footballers.

Group	Limb	Absolute eccentric hamstring strength (N)			Relative eccentric hamstring strength (N.kg^{-1})			Between limb imbalance (%)		
		Start of preseason	End of preseason	In-season	Start of preseason	End of preseason	In-season	Start of preseason	End of preseason	In-season
Injured	Injured	246 ± 79* (n=27)	284 ± 77* (n=17)	256 ± 157# (n=2)	3.04 ± 0.97* (n=27)	3.51 ± 0.95* (n=17)	3.16 ± 1.93# (n=2)	21.2 ± 23.8 (n=27)	13.1 ± 9.6 (n=17)	15.6 ± 4.9# (n=2)
	Uninjured	273 ± 89 (n=27)	292 ± 71* (n=17)	292 ± 169# (n=2)	3.37 ± 1.10* (n=27)	3.60 ± 0.87* (n=17)	3.61 ± 2.08# (n=2)			
Uninjured	Average of left and right	301 ± 84 (n=159)	330 ± 73 (n=157)	323 ± 80 (n=153)	3.81 ± 1.06 (n=159)	4.18 ± 0.92 (n=157)	4.09 ± 1.01 (n=153)	18.2 ± 20.8 (n=159)	10.5 ± 10.0 (n=157)	10.6 ± 11.0 (n=153)

Data presented as mean ± standard deviation. *Indicates significantly different to the uninjured group ($p<0.05$). #Indicates sample size from the injured group too small to make valid comparisons. Between limb imbalance determined as an absolute percentage (i.e. unidirectional)

Table 2. Univariate relative risk of sustain a future hamstring strain injury (HSI) using eccentric strength and imbalance, previous injury and demographic data as risk factors.

Risk factor	n	% from each group that sustained a HSI	Relative risk (95%CI)	p
Start of preseason eccentric strength	186			
< 256 N	72	23.6	2.7 (1.3 to 5.5)	0.006*
≥ 256 N	114	8.7		
< 3.16 $N.kg^{-1}$	66	25.8	3.1 (1.5 to 6.4)	0.002*
≥ 3.16 $N.kg^{-1}$	120	8.3		
Start of preseason strength imbalance	186			
< 10% imbalance	86	12.8	1.3 (0.6 to 2.5)	0.677
≥10% imbalance	100	16.0		
< 15% imbalance	113	14.2	1.0 (0.7 to 1.4)	1.000
≥15% imbalance	73	15.1		
< 20% imbalance	134	13.4	1.1 (0.8 to 1.5)	0.643
≥20% imbalance	52	17.3		
End of preseason eccentric strength	174			
< 279 N	52	21.2	4.3 (1.7 to 11.0)	0.002*
≥ 279 N	122	5.0		
<3.45 $N.kg^{-1}$	47	23.2	5.0 (1.9 to 12.6)	0.001*
≥ 3.45 $N.kg^{-1}$	127	4.7		
End of preseason strength imbalance	174			
< 10% imbalance	110	7.2	2.0 (0.8 to 4.8)	0.185
≥10% imbalance	64	14.1		
< 15% imbalance	129	8.5	1.2 (0.8 to 1.7)	0.385
≥15% imbalance	45	13.3		
< 20% imbalance	149	9.4	1.0 (0.8 to 1.3)	1.000
≥20% imbalance	26	11.5		

Prior injury	210			
HSI	34	23.5	2.1 (1.0 to 4.3)	0.093
No HSI	176	11.4		
ACL	19	26.3	2.2 (0.9 to 5.1)	0.146
No ACL	191	12.0		
Calf strain	15	13.3	1.0 (0.3 to 3.8)	1.000
No calf strain	195	13.3		
Quadriceps strain	8	25.0	1.9 (0.6 to 6.8)	0.601
No quadriceps strain	202	12.9		
Chronic groin pain	18	5.6	0.4 (0.1 to 2.7)	0.478
No chronic groin pain	192	14.1		
Age (years)	210			
≤ 18.9	21	9.5	1.4 (0.4 to 5.6)	0.747
> 18.9	189	13.8		
≤ 20.1	51	11.8	1.2 (0.5 to 2.7)	0.816
> 20.1	159	13.8		
≤ 22.6	105	10.5	1.5 (0.7 to 3.1)	0.310
> 22.6	105	16.2		
≤ 25.5	160	11.9	1.5 (0.7 to 3.1)	0.339
> 25.5	50	18.0		
≤ 28.9	189	13.2	1.1 (0.4 to 3.3)	1.000
> 28.9	21	14.3		
Height (cm)	210			
≤ 183 (reference)	59	20.3	1.0	
184 to 190	81	12.3	0.6 (0.3 to 1.3)	0.242
>190	70	8.6	0.4 (0.2 to 1.0)	0.074
Weight (kg)	210			

≤ 81 (reference)	46	17.4	1.0	
82 to 89	93	17.2	1.0 (0.5 to 2.1)	1.000
≥ 90	71	5.6	0.3 (0.1 to 1.0)	0.060

*indicates significant difference in relative risk of future hamstring strain injury between groups. 95%CI, 95% confidence interval; ACL, anterior cruciate ligament; cm, centimetres; HSI, hamstring strain injury; kg, kilograms; N, Newtons.

Table 3. Logistic regression model outputs and receiver operator characteristic curve data using previous hamstring strain injury (HSI), age and eccentric strength at the start of preseason as input variables.

		ChiSquare	p	AUC	Sensitivity	1 - Specificity
Model 1	Whole Model	9.69	0.021	0.674	0.5185	0.1887
	Prior HSI	1.83	0.176			
	Start of preseason eccentric strength#	7.23	0.007			
	Prior HSI x Start of preseason eccentric strength#	0.69	0.406			
Model 2	Whole Model	11.51	0.009	0.625	1.000	0.748
	Start of preseason eccentric strength#	7.15	0.008			
	Age	0.38	0.536			
	Age x Start of preseason eccentric strength#	5.00	0.025			

#Start of preseason eccentric strength determined as the average of both left and right limb forces.
AUC, area under the curve.