TITLE

Eccentric Knee-flexor Strength and Risk of Hamstring Injuries in Rugby Union: A Prospective Study

Authors

Matthew N. Bourne[1], David A. Opar[2], Morgan D. Williams[3], Anthony J. Shield[1].

[1]School of Exercise and Nutrition Sciences and the Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, Australia.

[2]School of Exercise Science, Australian Catholic University, Melbourne, Australia.

[3]School of Health, Sport and Professional Practice, University of South Wales, Wales, United Kingdom.

Corresponding Author

Dr Anthony Shield

School of Exercise and Nutrition Sciences and the Institute of Health and Biomedical
Innovation,
Queensland University of Technology, Victoria Park Road, Kelvin Grove, 4059,
Brisbane, Queensland, Australia.
Email: aj.shield@qut.edu.au
Ph: +61 7 3138 5829
Fax: +61 7 3138 3980

Running Title

Eccentric hamstring strength and injury risk

ABSTRACT

BACKGROUND: Hamstring strain injuries (HSIs) represent the most common cause of lost playing time in rugby union. Eccentric knee-flexor weakness and between-limb imbalance in eccentric knee-flexor strength are associated with a heightened risk of hamstring injury in other sports; however these variables have not been explored in rugby union. **PURPOSE:** To determine if lower levels of eccentric knee-flexor strength or greater between-limb imbalance in this parameter during the Nordic hamstring exercise are risk-factors for hamstring strain injury in rugby union. **STUDY DESIGN:** Cohort study; level of evidence, 3. **METHODS:** This prospective study was conducted over the 2014 Super Rugby and Queensland Rugby Union seasons. In total, 178 rugby union players (age, 22.6 ± 3.8 years; height, 185 ± 6.8 cm; mass, 96.5 ± 13.1 kg) had their eccentric knee-flexor strength assessed using a custom-made device during the pre-season. Reports of previous hamstring, quadriceps, groin, calf and anterior cruciate ligament injury were also obtained. The main outcome measure was prospective occurrence of hamstring strain injury. **RESULTS:** Twenty players suffered at least one hamstring strain during the study period. Players with a history of hamstring strain injury had 4.1 fold (RR = 4.1, 95% CI = 1.9 to 8.9, $p = 0.001$) greater risk of subsequent hamstring injury than players without such history. Between-limb imbalance in eccentric knee-flexor strength of $\geq 15\%$ and $\geq 20\%$ increased the risk of hamstring strain injury 2.4 fold (RR = 2.4, 95% CI = 1.1 to 5.5, $p = 0.033$) and 3.4 fold (RR = 3.4, 95% CI = 1.5 to 7.6, $p = 0.003$), respectively. Lower eccentric knee flexor strength and other prior injuries were not associated with increased risk of future hamstring strain. Multivariate logistic regression revealed that the risk of re-injury was augmented in players with strength imbalances. **CONCLUSION:** Previous hamstring strain injury and between-limb imbalance in eccentric knee-flexor strength were associated with an increased risk of future hamstring strain injury in rugby union. These results support the rationale for reducing imbalance, particularly in players who have suffered a prior hamstring injury, to mitigate the risk of future injury.

Key Terms

Injury prevention; Muscle injuries; Nordic hamstring exercise; Physical therapy/Rehabilitation; Rugby

What is known about the subject:

Hamstring strain injury (HSI) is the most common cause of lost playing and training time in professional rugby union and many of these injuries re-occur following a return to sport. Eccentric knee flexor weakness and between-limb imbalances in eccentric knee flexor strength have been associated with an increased risk of HSI in other sports, however, it remains to be seen if these are risk factors for HSI in rugby union.

What this study adds to the existing knowledge:

Rugby union players with between-limb imbalances in eccentric knee flexor strength in pre-season, and those with a history of HSI, are at a significantly elevated risk of future HSI. Moreover, for those players who have been injured previously, the risk of re-injury is amplified when they also have between-limb strength imbalances. This study highlights the multifactorial nature of HSI and supports the rationale for reducing strength imbalances, particularly in those players who have suffered a prior HSI.

INTRODUCTION

Rugby union is a physically demanding contact game with one of the highest reported incidences of match injuries of all sports.[7, 18, 40] The unique nature of the sport exposes athletes of varying anthropometric characteristics[45] to frequent bouts of high-intensity running, kicking, and unprotected collisions, interspersed with periods of lower intensity aerobic work.[14] Hamstring strain injury (HSI) represents the most common cause of lost playing and training time at the professional level[8, 9] and a significant portion of these injuries re-occur, resulting in extended periods of convalescence.[9]

Despite the prevalence of HSIs in rugby union,[8] efforts to identify risk factors and to optimise injury prevention strategies are limited.[9, 36] It is generally agreed that the aetiology of HSI is multifactorial[24] and injuries result from the interaction of several modifiable[10, 12, 13, 21, 28, 29, 33] and non-modifiable[2, 19, 20, 38] risk factors. In rugby union,[9] as well as several other sports,[3, 28, 41] HSIs most frequently result from high-speed running which potentially explains why the incidence of HSI is significantly higher for backline rugby players , who perform longer and more frequent sprints than forwards .[9] During running, the biarticular hamstrings play a crucial role in decelerating the forward swinging shank during terminal-swing[44] and in generating horizontal force upon ground contact.[23] Given the active lengthening role of the hamstrings it has been proposed that eccentric weakness[28] or between-limb imbalances in eccentric strength may predispose to HSI, and both factors have been associated with the risk of HSI in other sports.[13, 15, 21, 29, 42] Furthermore, interventions aimed at improving eccentric strength with the Nordic hamstring exercise reduce the incidence and severity of HSIs in soccer[1, 32] while professional rugby union teams employing the exercise have been reported to suffer fewer HSIs than those which do not.[9] Still, the role of eccentric strength in HSI occurrence remains a controversial issue with contradictory results reported in the literature[4, 46] and a recent meta-analysis suggested that isokinetically-derived measures of strength do not represent a risk factor for HSI.[17] Nevertheless, the authors are not aware of any study that has examined the relationship between eccentric knee-flexor strength, between-limb imbalance, and HSI incidence in rugby union. Given the unique anthropometric characteristics of rugby union players[45] and the diverse physical demands of the game,[14, 40] it may not be appropriate to generalise the findings from other sports to this cohort.

It has been shown that eccentric knee flexor strength can be reliably measured during the performance of the Nordic hamstring exercise.[26] In a recent prospective study of elite Australian footballers,[28] players with low Nordic strength measures in the pre-season training period were significantly more likely to sustain an HSI in the subsequent competitive season. However, it remains to be seen if the same measures can identify rugby union players at risk of future HSI.

An improved understanding of risk factors for HSI in rugby union represents the first step[37] towards optimising injury prevention strategies and reducing the high rates of HSI occurrence in the sport.[8, 9] The aim of this study was to determine whether pre-season eccentric knee-flexor strength and between-limb imbalance in strength measured during the Nordic hamstring exercise, were predictive of future HSI in rugby union players. In addition, given the multifactorial aetiology of HSI[24] and the potential for various risk factors to interact,[34] a secondary aim was to determine the association between measures of eccentric strength, imbalance and other previously identified risk factors, such as prior HSI.[9, 34] The *a priori* hypotheses were that subsequently injured players would display lower levels of eccentric knee-flexor strength and greater between-limb imbalances in this measure than players who remained free from HSI.

METHODS

Participants & study design

This prospective cohort study was approved by the Queensland University of Technology's Human Research Ethics Committee and was completed during the 2014 Super 15 and Queensland Rugby Union (QRU) seasons. In total, 194 male rugby players (age, 22.6 ± 3.8 years; height, 185 ± 6.7 cm; weight, 97 ± 13.1 kg) from three professional Super 15 clubs (n=75) and two local QRU clubs (n=119) provided written informed consent to participate. The QRU clubs included players in both sub-elite (n=79) and U'19 premier-grade teams (n=40). Prior to the commencement of data collection, retrospective injury details were collected for all players which included their history of hamstring, quadriceps and calf strain injuries and chronic groin pain within the preceding 12 months as well as history of anterior cruciate ligament (ACL) injury at any stage in their career. Demographic (age) and anthropometric (height, body mass) data were also collected in addition to player position (forward, back). For all Super 15 players these data were obtained from team medical staff and the national Australian Rugby Union registry. All sub-elite players completed a standard injury history form with their team physiotherapist and injuries were confirmed with information from each club's internal medical reporting system. Subsequently, players had their eccentric knee flexor strength assessed at a single time point within the 2014 pre-season (Super 15, November 2013; sub-elite, January 2014). At the discretion of team medical staff, some players (n=16) were excluded from strength testing because they had an injury or illness at the time of testing that precluded them from performing maximal resistance exercise

Eccentric knee-flexor strength assessment

The assessment of eccentric knee-flexor strength during the Nordic hamstring exercise has been reported previously.[26, 28] 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) (Figure 1). The ankle braces and load cells were secured to a pivot which allowed the force generated by the knee flexors to always be measured through the long axis of the load cells. Immediately prior to testing, players were provided with a demonstration of the Nordic hamstring exercise from investigators and received the following instructions: gradually lean forward at the slowest possible speed while maximally resisting this movement with both limbs while keeping the trunk and hips in a neutral position throughout, and the hands held across the chest[28]. Subsequently, players completed a single warm-up set of three repetitions followed by one set of three maximal repetitions of the bilateral Nordic hamstring exercise. All trials were closely monitored by investigators to ensure strict adherence to proper technique and players received verbal encouragement throughout each repetition to encourage maximal effort. A repetition 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. All eccentric strength testing was performed in a rested state, prior to the commencement of scheduled team training.

INSERT FIGURE 1

Data analysis

Force data for the left and right limbs were transferred to a personal computer at 100Hz through a wireless USB base station receiver (Mantracourt, Devon, UK). Eccentric strength, determined for each leg from the peak force during the best of three repetitions of the NHE, was reported in absolute terms (N) and relative to bodyweight ($N.kg^{-1}$). For the uninjured group, between limb imbalance in peak eccentric knee-flexor force was calculated as a left:right limb ratio and for the injured group, as an uninjured:injured limb ratio. The between limb imbalance ratio was converted to a percentage difference as per previous work[28] using log transformed raw data followed by back transformation.

Prospective hamstring strain injury reporting

An HSI was defined as acute pain in the posterior thigh which caused immediate cessation of training or match play and damage to the hamstring muscle-tendon unit[28] which was later confirmed with magnetic resonance imaging (for all Super 15 players) or clinical examination by the team physiotherapist (for all sub-elite and U'19 players). For all injuries that satisfied the inclusion criteria, team medical staff provided the following details to investigators: limb injured (left / right), muscle injured (biceps femoris long or short head/semimembranosus/semitendinosus, injury severity (grade 1-3), injury mechanism (ie, running, kicking, collision, change of direction), the date of injury and whether it was a recurrence and the total time taken to resume full training and competition.

Statistical analysis

All statistical analyses were performed using JMP 10.02 (SAS Institute, Inc). Mean and standard deviations (SD) of age, height, weight, eccentric knee-flexor strength for the left and right limb and between-limb imbalance (%) in strength were determined. Because the player and not the leg was the unit of measure in some analyses, it was necessary to have a single measure of eccentric knee-flexor strength for each athlete and this was determined by averaging the peak forces from each limb (two-limb-average strength). Univariate analysis was used to compare age, height, weight and between-limb imbalance between the injured and uninjured groups. Eccentric knee-flexor strength of the injured limb was compared to the uninjured contralateral limb and to the average of the left and right limbs from the uninjured control group. In addition, eccentric knee-flexor strength was compared between elite, sub-elite and U'19 players and between player positions (forwards vs. backs). All univariate comparisons were made using independent samples t tests with Bonferroni corrections to control for Type 1 error.

To calculate univariate relative risk (RR) and 95% confidence intervals (95% CI), players were grouped according to:

- whether they did or did not have a history of
    - HSI in the previous 12 months
    - quadriceps strain injury in the previous 12 months
    - chronic groin pain in the previous 12 months
    - calf strain injury in the previous 12 months
    - or ACL injury at any stage;

- Two-limb-average eccentric knee-flexor strength above or below 267.9N or 3.18N.kg^{-1} (these cut-offs were determined using receiver operator characteristic (ROC) curves based on the force and relative force values that maximised the difference between sensitivity and 1 – specificity).

- between-limb eccentric strength imbalance above or below a 10, 15 or 20% cut-off;

- whether they were above or below the 25th, 50th and 75th percentiles for:

  - age
  - height
  - weight

Any variable associated with subsequent HSI according to univariate analysis was entered into a univariate logistic regression model to determine its predictive value as a risk factor for future HSI. Furthermore, given the multifactorial nature of HSI, a multivariate logistic regression model was constructed (using prior HSI and between-limb imbalance) to explore the potential interaction between risk factors[28] and eliminate any confounding effects.[30] Alpha was set at $p<0.05$ and for all univariate analyses the difference between limbs and groups is reported as mean difference and 95% CI.

RESULTS

Cohort and prospective hamstring strain injury details

In total, 178 players (age, 22.6 ± 3.8 years; height, 185 ± 6.8 cm; weight, 96.5 ± 13.1 kg) had their eccentric knee-flexor strength assessed in the pre-season period. Of these, 75 were elite (age, 24.4 ± 3.1 years; height, 186 ± 7.2 cm; weight, 101 ± 11.3 kg), 65 were sub-elite (age, 21.3 ± 3.7 years; height, 184 ± 6.4 cm; weight, 93 ± 13.4 kg) and 38 were in the U'19 division (age, 18.1 ± 0.8 years; height, 183 ± 6.8 cm; weight, 91 ± 14.9 kg).

Twenty athletes suffered at least one HSI during the 2014 competitive season (age, 22.8 ± 3.2 years; height, 185.6 ± 5.5 cm; weight, 97.4 ± 12.4 kg) and 158 remained free of HSI (age, 22.5 ± 3.8 years; height, 184.9 ± 7.0 cm; weight, 96.4 ± 13.3 kg). No significant differences were observed in terms of age, height or body mass between the subsequently injured and uninjured players (p>0.05). Hamstring strains resulted in an average of 21 days (range = 7 to 49 days) absence from full training and match play. Forty-five percent were recurrences from the previous season and 25% of those reported during the observation period recurred. Of the 20 injuries, 80% affected the biceps femoris as the primary site of injury and 85% resulted from high-speed running. The majority of HSIs were sustained by backs (60%) compared to forwards (40%). No injuries were sustained during the assessment of eccentric knee-flexor strength.

Comparison of strength between playing level and position

Eccentric strength measures for each level of play and player position can be found in Table 1. In terms of eccentric strength, there was no significant difference between elite and sub-elite players (mean difference = 21N, 95% CI = -7.8 to 49.9N, p = 0.154) or between elite and U’19 players (mean difference = 24.1N, 95% CI = -6.90 to 55.0 N, p = 0.126) however, sub-elite players were significantly stronger than U’19 players (mean difference 45.1N, 95% CI = 8.1 to 82.0N, p = 0.017). When expressed relative to bodyweight, both sub-elite (mean difference = 0.35, 95%CI = 0.08 to 0.63, p = 0.013) and U’19 players (mean difference = 0.38N, 95%CI = 0.07 to 0.70, p = 0.017) were significantly stronger than elite players although no difference was observed between sub-elite and U’19 players (mean difference = -0.03, 95%CI = -0.4 to 0.34, p = 0.870). In absolute terms, forward line players were significantly stronger than backs (mean difference = 35.3N, 95% CI = 10.11 to 60.5N, p= 0.006) however, no difference was observed when strength was normalised to bodyweight (mean difference = -0.1, 95%CI = -0.35 to 0.16, p = 0.583).

INSERT TABLE 1

Univariate analysis of factors associated with hamstring strain injury

Eccentric knee-flexor strength and between-limb imbalances for the injured and uninjured groups can be found in Table 2. Limbs that went on to be injured were significantly weaker in pre-season than uninjured contralateral limbs both in absolute terms (mean difference = 55.1N, 95% CI = 11.65 to 98.5N, p=0.016) and when normalised to body mass (mean difference = 0.55 N.kg^{-1}, 95% CI = 0.13 to 0.98N.kg^{-1}, p = 0.013). Players who went on to sustain an HSI displayed higher levels of between-limb imbalance than those players who remained free from HSI (mean difference = -7.4%, 95% CI = -12.4 to -2.4%, p = 0.004). However, there was no difference between the subsequently injured limb and the average of the left and right limbs from the uninjured group either in absolute strength (mean difference = -14.9N, 95% CI = -55.5 to 25.6N, p = 0.470) or strength relative to body mass (mean difference = -0.07 N.kg^{-1}, 95% CI = -0.48 to 0.33 N.kg^{-1}, p = 0.710). No significant differences were observed in age (mean difference = 0.18yrs, 95% CI = -1.5 to 1.9yrs, p = 0.235), height (mean difference = 0.86cm, 95% CI = -2.3 to 4.1cm, p = 0.457), or weight (mean difference = 0.97kg, 95% CI = -5.2 to 7.4kg, p = 0.632) between the injured and uninjured groups.

INSERT TABLE 2

Relative risk

Players with a history of HSI in the previous 12 months had 4.1 (RR = 4.1, 95% CI = 1.9 to 8.9, p = 0.001) times greater risk of suffering a subsequent HSI than players with no HSI in the same period (Table 2). Between-limb imbalance in eccentric knee-flexor strength of ≥ 15% increased the risk of HSI 2.4 fold (RR = 2.4, 95% CI = 1.1 to 5.5, p = 0.033) while an imbalance ≥ 20% increased that risk 3.4 fold (RR = 3.4, 95% CI = 1.5 to 7.6, p = 0.003). However, players with two-limb-average eccentric knee-flexor strength of less than 267.9N were not at elevated risk of HSI (RR = 0.17, 0.0 to 2.7, p=0.204) compared to stronger players (area under the ROC curve = 0.52; specificity= 0.86; sensitivity = 1.0). Similarly, having normalised strength values of less than 3.18N.kg^{-1} did not increase the risk of HSI (RR = 0.97, 95%CI = 0.3 to 2.7, p = 0.957).

INSERT TABLE 3

Logistic regression

Players with a history of HSI in the previous 12 months were, according to the odds ratio, 5.3 times more likely (OR = 5.3, 95%CI = 1.84 to 15.0, p = 0.003) to suffer a subsequent HSI than players who had remained injury free in that time. In addition, a relationship was observed between the magnitude of between-limb imbalance in eccentric knee-flexor strength and the risk of subsequent HSI; where, for every 10% increase in between-limb imbalance, the odds of HSI increased by a factor of 1.34 (95%CI = 1.03 to 1.75, p=0.028) (Figure 2).

INSERT TABLE 4

Multivariate logistic regression revealed a significant (<0.001) relationship between both prior HSI and between-limb imbalance and the risk of subsequent HSI (Table 4), however, no interaction effect was observed between these variables. This model suggests that for players with a history of HSI, the risk of re-injury is amplified when they also have between-limb imbalances in eccentric knee flexor strength (Figure 2).

INSERT FIGURE 2

DISCUSSION

The aim of this study was to determine if rugby union players with lower levels of eccentric strength or larger between-limb imbalances in this measure, as determined during the Nordic hamstring exercise, were at increased risk of HSI. Higher levels of between-limb imbalance were found to significantly increase the risk of subsequent HSI and this was amplified in athletes who had suffered the same injury in the previous 12 months. However, while the limbs that went on to be injured were significantly weaker than the uninjured contralateral limbs in pre-season testing, weaker players were no more likely to suffer injury than stronger players when strength was determined by averaging the peak eccentric forces from left and right limbs.

The observation that higher levels of between-limb strength imbalance increase an athlete's risk of HSI is consistent with previous reports.[13, 15, 21, 29, 42] Croisier and colleagues reported that professional soccer players with isokinetically-derived knee-flexor strength imbalances in pre-season had a 4.66 fold greater risk of subsequent HSI than athletes without such imbalances. More recently, Fousekis and colleagues found that elite soccer players with imbalances in eccentric knee-flexor strength ≥ 15% in the pre-season had a significantly greater (OR = 3.88) risk of HSI than athletes with no asymmetry.[15] Still, contradictory results have been reported in Australian footballers[4, 28] and it remains unclear as to the exact mechanism(s) by which significant imbalances increase the risk of HSI. It is plausible that between-limb imbalances in eccentric knee-flexor strength may alter running biomechanics[11] or reduce the capacity of the weaker limb to decelerate the forward swinging shank during terminal-swing.[25] However, it should also be noted that the assessment of between-limb imbalance in the current study was performed during a bilateral Nordic hamstring exercise, whereas typical assessments involve maximal unilateral contractions performed on an isokinetic dynamometer.[4, 15] For this reason, direct comparisons to previous work should be made with caution. A bilateral Nordic hamstring exercise was employed in the current study as previous work has shown that this is more a more reliable test of eccentric knee-flexor strength than unilateral Nordics .[26]

The finding that weaker players were no more likely to sustain an HSI than stronger players is in line with a recent systematic review and meta-analysis which suggested that isokinetically-derived measures of strength were not a risk factor for HSI in sport.[17] However, the results of the current study differ from a recent investigation[28] using the Nordic hamstring test which reported that elite Australian footballer's with eccentric strength <256N at the start of preseason and <279N at the end of preseason had a 2.7 and 4.3 fold greater risk of HSI, respectively. The disparity between studies might reflect the vastly different anthropometric characteristics of rugby union[45] and Australian football players,[5] or the unique physical demands of each sport.[14, 31] However, it is also important to consider that the rugby players in the current study were substantially stronger than the Australian footballer's studied previously.[28] It is possible that the protective benefits conferred by greater levels of eccentric strength may plateau at higher ends of the strength spectrum as they appear to in Australian footballer's (see Figures 1 & 2 in Opar et al.).[28] It should also be acknowledged that while some studies have found an association between low levels of knee-flexor strength and subsequent HSI,[21, 28, 42] prior injury is also associated with knee-flexor weakness,[12, 22, 26, 27, 35] and this may confound results.[30]

The current study supports prior HSI as a risk factor for re-injury which is consistent with earlier observations in rugby union[9, 36] Australian football[4, 16, 30, 39] and soccer.[2] While the mechanism(s) explaining why prior HSI augments the risk of re-injury remain(s) unclear, this study revealed a significant relationship between prior HSI and between-limb imbalance in eccentric knee-flexor strength. This novel finding suggests that rugby union players with a history of HSI have a significantly greater risk of re-injury if they return to training and match play with one limb weaker than the other (Figure 2). For example, an athlete with a prior HSI and a 30% between-limb imbalance in eccentric strength is twice as likely to suffer a recurrence as a previously injured athlete with no imbalance. In light of this interaction, there is a growing body of evidence to suggest that between-limb imbalance in knee-flexor strength[12, 13, 22, 29] is a risk-factor for HSI recurrence. These data highlight the multifactorial nature of HSIs and suggest that the amelioration of between-limb imbalances in eccentric knee-flexor strength should be a focus of rehabilitative strategies following HSI.

There are some limitations that should be acknowledged in the current study. Firstly, the assessment of eccentric knee-flexor strength and between-limb imbalance was only performed at a single time point in the pre-season period. While this is consistent with other prospective studies exploring the impact of strength variables on HSI risk,[13, 15, 21, 29, 42] it is important to consider that strength may change over the pre-season and in-season periods.[28] The assessment of strength at multiple time points may provide a more robust measure of player risk however, the geographic diversity of the Super 15 competition precluded follow-up assessments by the investigators. Eccentric strength was measured as a force output (N) rather than a joint torque (Nm) which makes direct comparison to isokinetically-derived measures difficult. Further, this mode of testing does not allow for an assessment of the angle at which the knee flexors produce maximum torque,[6] and did not permit force to be expressed relative to quadriceps[13] or hip flexor[43] strength, which may provide additional information on an athlete's risk of HSI. Finally, the lack of player exposure data prevents HSI rates being expressed relative to the amount of training and match-play. Future work should seek to clarify the effect of total exposure time (particularly to high-speed running) on the incidence of HSI in rugby union players.[9]

In conclusion, this study suggests that both between-limb imbalances in eccentric knee-flexor strength and prior HSI are associated with an increased risk of future HSI in rugby union. However, lower levels of eccentric knee-flexor strength and a recent history of other lower limb injuries do not significantly increase the risk of future HSI in this cohort. This study, along with previous findings,[28] highlights the multifactorial nature of HSI and supports the rationale for reducing imbalance, particularly in players who have suffered a prior injury within the previous 12 months.

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References

1. Arnason A, Andersen TE, Holme I, Engebretsen L, Bahr R. Prevention of hamstring strains in elite soccer: an intervention study. *Scand J Med Sci Sports.* 2008;18(1):40-48. [Medline]

2. Arnason A, Sigurdsson SB, Gudmundsson A, Holme I, Engebretsen L, Bahr R. Risk factors for injuries in football. *Am J Sports Med.* 2004;32(1 Suppl):5S-16S. [Medline]

3. Askling CM, Tengvar M, Saartok T, Thorstensson A. Acute first-time hamstring strains during high-speed running: a longitudinal study including clinical and magnetic resonance imaging findings. *Am J Sports Med.* 2007;35(2):197-206. [Abstract/Full Text]

4. Bennell K, Wajswelner H, Lew P, et al. Isokinetic strength testing does not predict hamstring injury in Australian Rules footballers. *Br J Sports Med.* 1998;32(4):309-314. [Medline]

5. Bilsborough JC, Greenway K, Opar D, et al. Comparison of anthropometry, upper body strength and lower body power characteristics in different levels of Australian Football players. *J Strength Cond Res.* 2014. [Medline]

6. Brockett CL, Morgan DL, Proske U. Predicting hamstring strain injury in elite athletes. *Med Sci Sports Exerc.* 2004;36(3):379-387. [Medline]

7. Brooks JH, Kemp SP. Recent trends in rugby union injuries. *Clin Sports Med.* 2008;27(1):51-73, vii-viii. [Medline]

8. Brooks JHM, Fuller CW, Kemp SPT, Reddin DB. Epidemiology of injuries in English professional rugby union: part 1 match injuries. *Br J Sports Med.* 2005;39:757-766. [Abstract/Full Text]

9. Brooks JHM, Fuller CW, Kemp SPT, Reddin DB. Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. *Am J Sports Med.* 2006;34(8):1297-1306. [Abstract/Full Text]

10. Burkett LN. Causative factors in hamstring strains. *Med Sci Sports Exerc.* 1970;2(1):39-42.

11. Chumanov ES, Heiderscheit BC, Thelen DG. The effect of speed and influence of individual muscles on hamstring mechanics during the swing phase of sprinting. *J Biomech.* 2007;40(16):3555-3562. [Medline]

12. Croisier JL, Forthomme B, Namurois MH, Vanderthommen M, Crielaard JM. Hamstring muscle strain recurrence and strength performance disorders. *Am J Sports Med.* 2002;30(2):199-203. [Abstract/Full Text]

13. Croisier JL, Ganteaume S, Binet J, Genty M, Ferret JM. Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. *Am J Sports Med.* 2008;36(8):1469-1475. [Medline]

14. Duthie G, Pyne D, Hooper S. Applied physiology and game analysis of rugby union. *Sports Med.* 2003;33(13):973-991. [Medline]

15. Fousekis K, Tsepis E, Poulmedis P, Athanasopoulos S, Vagenas G. Intrinsic risk factors of non-contact quadriceps and hamstring strains in soccer: a prospective study of 100 professional players. *Br J Sports Med.* 2011;45(9):709-714. [Medline]

16. Freckleton G, Cook J, Pizzari T. The predictive validity of a single leg bridge test for hamstring injuries in Australian Rules Football Players. *Br J Sports Med.* 2014;48(8):713-717. [Medline]

17. Freckleton G, Pizzari T. Risk factors for hamstring muscle strain injury in sport: a systematic review and meta-analysis. *Br J Sports Med.* 2013;47(6):351-358. [Medline]

18. Fuller CW, Sheerin K, Targett S. Rugby World Cup 2011: International Rugby Board injury surveillance study. *Br J Sports Med.* 2013;47(18):1184-1191. [Medline]

19. Gabbe B, Bennell K, Finch C, Wajswelner H, Orchard J. Predictors of hamstring injury at the elite level of Australian football. *Scand J Med Sci Sports.* 2006;16:7-13. [Medline]

20. Hagglund M, Walden M, Ekstrand J. Previous injury as a risk factor for injury in elite football: a prospective study over two consecutive seasons. *Br J Sports Med.* 2006;40(9):767-772. [Medline]

21. Heiser TM, Weber J, Sullivan G, Clare P, Jacobs RR. Prophylaxis and management of hamstring muscle injuries in intercollegiate football players. *Am J Sports Med.* 1984;12(5):368-370. [Abstract]

22. Jonhagen S, Nemeth G, Eriksson E. Hamstring Injuries in Sprinters. The role of concentric and eccentric hamstring muscle strength and flexibility. *Am J Sports Med.* 1994;22:262. [Abstract]

23. Mann RA, Moran GT, Dougherty SE. Comparative electromyography of the lower extremity in jogging, running, and sprinting. *Am J Sports Med.* 1986;14(6):501-510. [Medline]

24. Mendiguchia J, Alentorn-Geli E, Brughelli M. Hamstring strain injuries: are we heading in the right direction? *Br J Sports Med.* 2012;46(2):81-85. [Medline]

25. Opar D, Williams M, Shield A. Hamstring strain injuries: Factors that lead to injury and re-injury. *Sports Med.* 2012;42(3):209-226. [Medline]

26. Opar DA, Piatkowski T, Williams MD, Shield AJ. A novel device using the Nordic hamstring exercise to assess eccentric knee flexor strength: a reliability and retrospective injury study. *J Orthop Sports Phys Ther.* 2013;43(9):636-640. [Medline]

27. Opar DA, Williams MD, Timmins RG, Dear NM, Shield, AJ. Knee flexor strength and bicep femoris electromyographical activity is lower in previously strained hamstrings. *J Electromyogr and Kinesiol*. 2013; 23(3):696-703.

28. Opar DA, Williams MD, Timmins RG, Hickey J, Duhig SJ, Shield AJ. Eccentric hamstring strength and hamstring injury risk in Australian footballers. *Med Sci Sports Exerc*. 2014. [Medline]

29. Orchard J, Marsden J, Lord S, Garlick D. Preseason hamstring muscle weakness associated with hamstring muscle injury in Australian footballers. *Am J Sports Med.* 1997;25(1):81-85. [Medline]

30. Orchard JW. Intrinsic and extrinsic risk factors for muscle strains in Australian football. *Am J Sports Med.* 2001;29(3):300-303. [Medline]

31. Orchard JW, Seward H, Orchard JJ. Results of 2 decades of injury surveillance and public release of data in the Australian Football League. *Am J Sports Med.* 2013;41(4):734-741. [Medline]

32. Petersen J, Thorborg K, Nielsen MB, Budtz-Jørgensen E, Hölmich P. Preventive effect of eccentric training on acute hamstring injuries in men's soccer a cluster-randomized controlled trial. *Am J Sports Med.* 2011;39(11):2296-2303. [Abstract/Full Text]

33. Sugiura Y, Saito T, Sakuraba K, Sakuma K, Suzuki E. Strength deficits identified with concentric action of the hip extensors and eccentric action of the hamstrings predispose to hamstring injury in elite sprinters. *J Orthop Sports Phys Ther.* 2008;38(8):457-464. [Medline]

34. Thorborg K. What are the most important risk factors for hamstring muscle injury? *Clin J Sport Med.* 2014;24(2):160-161. [Medline]

35. Timmins RG, Shield AJ, Williams MD, Lorenzen C, Opar DA. Biceps femoris long head architecture: a reliability and retrospective injury study. *Med Sci Sports Exerc.* 2015*;* 47(5):905-13.

36. Upton PA, Noakes TD, Juritz JM. Thermal pants may reduce the risk of recurrent hamstring injuries in rugby players. *Br J Sports Med.* 1996;30(1):57-60. [Medline]

37. van Mechelen W, Hlobil H, Kemper HC. Incidence, severity, aetiology and prevention of sports injuries. A review of concepts. *Sports Med.* 1992;14(2):82-99. [Medline]

38. Verrall GM, Slavotinek JP, Barnes PG, Fon GT, Spriggins AJ. Clinical risk factors for hamstring muscle strain injury: a prospective study with correlation of injury by magnetic resonance imaging. *Br J Sports Med.* 2001;35(6):435-439. [Medline]

39. Warren P, Gabbe BJ, Schneider-Kolsky M, Bennell KL. Clinical predictors of time to return to competition and of recurrence following hamstring strain in elite Australian footballers. *Br J Sports Med.* 2010;44(6):415-419. [Medline]

40. Williams S, Trewartha G, Kemp S, Stokes K. A meta-analysis of injuries in senior men's professional Rugby Union. *Sports Med.* 2013;43(10):1043-1055. [Medline]

41. Woods C, Hawkins RD, Maltby S, Hulse M, Thomas A, Hodson A. The Football Association Medical Research Programme: an audit of injuries in professional football--analysis of hamstring injuries. *Br J Sports Med.* 2004;38(1):36-41. [Abstract/Full Text]

42. Yamamoto T. Relationship between hamstring strains and leg muscle strength. A follow-up study of collegiate track and field athletes. *J Sports Med Phys Fitness.* 1993;33(2):194-199. [Medline]

43. Yeung S, Suen A, Yeung E. A prospective cohort study of hamstring injuries in competitive sprinters: preseason muscle imbalance as a possible risk factor. *Br J Sports Med.* 2009;43:589-594. [Medline]

44. Yu B, Queen R, Abbey A, Liu Y, Moorman C, Garrett W. Hamstring muscle kinematics and activation during overground sprinting. *J Biomech.* 2008;41:3121-3126. [Medline]

45. Zemski AJ, Slater GJ, Broad EM. Body composition characteristics of elite Australian rugby union athletes according to playing position and ethnicity. *J Sports Sci.* 2015:1-9. [Medline]

46. Zvijac JE, Toriscelli TA, Merrick S, Kiebzak GM. Isokinetic concentric quadriceps and hamstring strength variables from the NFL Scouting Combine are not predictive of hamstring injury in first-year professional football players. *Am J Sports Med.* 2013;41(7):1511-1518. [Medline]

Figure legends

Figure 1. The Nordic hamstring exercise performed on the testing device (progressing from right to left). Participants were instructed to lower themselves to the ground as slowly as possible by performing a forceful eccentric contraction of their knee flexors. Participants only performed the eccentric portion of the exercise and after ‘catching their fall’, were instructed to use their arms to push back into the starting position (not shown here). The ankles are secured independently.

Figure 2. The relationship between eccentric knee flexor strength imbalances and probability of future hamstring strain injury (HSI) for players with and without a history of HSI in the previous 12 months. Errors bars depict 95% confidence intervals.