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Anterior cruciate ligament reconstruction increases the risk of hamstring strain injury across football codes in Australia

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Title:

Anterior cruciate ligament reconstruction increases the risk of hamstring strain injury across football codes in Australia

Running Title: Hamstring strain risk after prior injury

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Abstract

Objective: To determine the impacts of anterior cruciate ligament reconstruction (ACLR) and recent (< 12 months) hamstring strain injury (HSI) on 1) future HSI risk ; and 2) eccentric knee flexor strength and between-limb imbalance during the Nordic hamstring exercise (NHE). A secondary goal was to examine whether eccentric knee flexor strength was a risk factor for future HSI in athletes with prior ACLR and/or HSI. **Methods:** In this prospective cohort study, 531 male athletes had preseason eccentric knee flexor strength tests. Injury history was also collected. The main outcome was HSI occurrence in the subsequent competitive season. **Results:** 74 athletes suffered at least one prospective HSI. Compared to control athletes, those with a life-time history of ACLR and no recent HSI had 2.2 (95%CI=1.1-4.4; $p = 0.029$) times greater odds of subsequent HSI while those with at least one HSI in the previous 12 months and no history of ACLR had 3.1 (95%CI=1.8-5.4; $p < 0.001$) times greater odds for subsequent HSI. Only athletes with a combined history of ACLR and recent HSI had weaker injured limbs ($p = 0.001$) and larger between-limb imbalances ($p < 0.001$) than uninjured players. An exploratory decision tree analysis suggested eccentric strength may protect against HSI after ACLR. **Conclusion:** ACLR and recent HSI were similarly predictive of future HSI. Lower levels of eccentric knee flexor strength and larger between-limb imbalances were found in athletes with combined histories of ACLR and recent HSI. These findings may have implications for injury rehabilitation.

Key Points:

- A prior anterior cruciate ligament injury requiring reconstruction, like a previous hamstring strain injury, is a predictor of future hamstring strain injury.
- Athletes who had experienced ACLR without hamstring strain injury in the past 12 months or hamstring injury without ACLR did not exhibit eccentric strength deficits. Only athletes with both a lifetime history of ACLR and a hamstring strain injury in the past 12 displayed deficits in eccentric strength.
- High levels of eccentric knee flexor strength may protect against hamstring strain injury for those athletes with a prior history of anterior cruciate ligament injury requiring reconstruction.

1.0 Introduction

Anterior cruciate ligament (ACL) injuries and hamstring strain injuries (HSIs) account for a significant amount of lost playing time in a range of football codes such as soccer, Rugby and Australian Rules football [1, 2]. They have high recurrence rates [1] and a history of each injury is a very strong predictor of the same type of injury in the future [3]. It has also been suggested that a history of a significant knee injury is a risk factor for HSI [4], although the evidence for a link between past ACL reconstruction (ACLR) and future hamstring injury is limited [5].

A number of studies have reported deficits in concentric [6] and eccentric [7, 6] knee flexor strength, semitendinosus muscle size [8] and fascicle length within the biceps femoris long head [7] in the years following ACLR surgery. However, these studies are almost always constrained by small sample sizes and several investigations have found conflicting results regarding the recovery of strength after rehabilitation [9, 10]. The recovery of strength may also be dependent on the level of sports participation and there is currently little data on the eccentric strength levels of well-trained (elite and near-elite) athletes who have undergone ACLR and have returned to full sports participation.

Preseason deficits in eccentric knee flexor strength during the Nordic hamstring exercise (NHE) have been associated with an increased risk of future hamstring injury in elite Australian rules footballers [11] and Australian soccer players [12], although no such relationship was noted for Rugby players [13], Gaelic football players [14] or Qatari soccer players [15]. However, interactions between previous HSI history and eccentric strength have been reported, with weakness appearing to have a more significant effect on future injury rates in previously injured than uninjured athletes [11, 12]. At present, however, it is unknown whether eccentric knee flexor strength has an impact on the likelihood of future HSI in athletes with a history of ACLR.

The primary goals of this study were to determine the impact of a prior ACLR, HSI or both on (1) the risk of future HSI and (2) eccentric knee flexor strength and between-limb imbalance as measured during the NHE. A secondary goal was to examine whether eccentric knee flexor strength was a risk factor in future HSI. We hypothesised; (1) that athletes with prior ACLR and/or HSI would be at an increased risk of future HSI when compared to those with no such injury history, and (2) that prior ACLR and recent HSI would be associated with deficits in eccentric knee flexor strength.

2.0 Methods

2.1 Participants and study design

This study involved a secondary analysis of data collected between 2013 and 2015 for three previously published prospective studies [11, 13, 12]. Ethics approval for these studies was granted by the Queensland University of Technology Human Research Ethics Committee and the Australian Catholic University Human Research Ethics Committee. From these combined studies, a total of 535 male athletes, including 210 elite Australian Football League (AFL) players, 147 elite A-League soccer players (goalkeepers included), and 75 elite and 103 sub-elite rugby union players were included for observation (see Figure 1). Four players from the AFL cohort were removed from the analysis due to incomplete strength testing data. In total, 531 male athletes were included in the analysis. All three studies required players and/or team medical staff to complete a previous injury questionnaire that documented each athlete's history of hamstring, quadriceps, and calf strain injuries and chronic groin pain within the previous 12 months, in addition to their lifetime history of ACLR. These injury reports were confirmed with information from each club's internal medical recording system or consultation between players and an investigator in the case of sub-elite rugby players. The type of ACLR was not recorded for the AFL cohort or some of the rugby players and in all cases the year the injury occurred was recorded but not the specific time point. This study deals with the effects of ACLR on subsequent hamstring injury rather than the effects of any specific reconstruction technique.

2.2 Experimental design

2.2.1 Eccentric knee flexor strength

The assessment of eccentric knee flexor strength using the Nordic hamstring testing device has been reported previously [16, 11, 12, 17]. Athletes knelt over a padded board, with 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 generated by the knee flexors to be measured through the long axis of the load cells. Following a warm up set of three submaximal repetitions (at ~70, 80 % 90% of perceived maximum effort), athletes performed one set of three maximal repetitions of the bilateral NHE. Athletes were instructed to lean forward at the slowest possible speed while maximally resisting this movement with both limbs and keeping the trunk and hips in a neutral position throughout, with the hands held in line with the chest. Athletes were loudly encouraged to provide maximum effort during each repetition. A repetition was considered 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.

2.3 Data analysis

Force data for each limb were transferred to a personal computer at 100 Hz through a wireless USB base station receiver (Mantracourt, Devon, UK). Eccentric knee flexor strength, determined for each leg from the peak forces during three repetitions of the NHE, was reported in absolute terms (N). For athletes with no history of lower limb injury, a between-limb imbalance in peak eccentric knee flexor force was calculated as a right:left limb ratio and, for athletes with a prior ACLR or HSI as an uninjured:injured limb ratio. The between-limb imbalance ratio was converted to a percentage difference as per previous work [13, 11] using log-transformed raw data, followed by back transformation. Negative percentage imbalances specify that the left limb was stronger than the right limb in athletes with no history of lower limb injury or that the previously injured limb was stronger than the uninjured limb in athletes with a prior ACLR or HSI. Participants were categorised into groups based on their injury histories (see Figure 1) and were excluded if they had insufficient injury history or strength testing data.

INSERT FIGURE 1 HERE

Figure 1. Participant recruitment and inclusion in the study. 1) No prior anterior cruciate ligament injury (ACL) at any stage and no hamstring strain injury (HSI) within the previous 12 months, 2) At least one HSI in the previous 12 months, 3) At least one ACL injury requiring reconstructive surgery at any stage in the athlete's life.

2.4 Statistical analyses

All statistical analyses were performed using JMP 10.2.0 Statistical Discovery Software (SAS Inc., Cary, North Carolina, USA). Means and standard deviations (SDs) of age, height, body mass, eccentric knee flexor strength for the left and right limbs, and between limb imbalance (%) in strength were determined. The eccentric knee flexor strength of the injured limb in athletes with a history of ACLR and/or HSI were compared with the uninjured contralateral limbs and the average of the left and right limbs (the two-limb average) in athletes with no history of ACLR or HSI. The decisions to average results from left and right limbs were made a priori, although subsequent analyses revealed no statistically significant differences between strength measures from the left and right limbs in athletes with no history of ACLR and no recent HSI [11,12,13]. Analyses of covariance (ANCOVA) were performed to assess the effect of prior ACLR, HSI or both on i) eccentric knee flexor strength using body mass as the covariate, and ii) between limb imbalance using the uninjured limb peak force as the covariate. All post-hoc comparisons were made using independent-samples *t* tests with Bonferroni corrections to control for type 1 errors and reported as the mean difference (95% CIs). Pearson's correlation (R^2) was used to assess the magnitude of eccentric knee flexor strength deficits with time since ACLR and was reported with the 95% CI. Univariate logistic regression was performed on the following variables: prior HSI, prior ACLR, peak eccentric knee flexor strength (average of left and right limb), between limb imbalance, age and body mass to assess the contribution of each variable to future injury risk. All variables were then added to a multivariable logistic regression model to assess the risk of future HSI. Odds ratios (95% CIs) were reported for all variables. For these analyses, eccentric knee flexor strength was not scaled to body mass because both variables were examined independently. Given the relatively low number of HSIs reported in this cohort, a Decision Tree Induction (DTI) was conducted to look at the inter-relationship between predictive variables and to visualise the data as an additional form of analysis. Unlike linear models, the DTI maps non-linear relationships effectively and can handle categorical and numerical data for classification and regression. The DTI was applied to those variables included in the final multivariable logistic regression model, thus providing further exploration of the possible effects of those factors on HSI risk. The size of the contribution of each factor was assessed by Gina square (G^2, where higher values indicate factors that make a greater contribution to injury risk) and injury risk was assessed by the magnitude of the probability (Prob). Body mass was included as a covariate in the analysis of covariance given the potential relationship between eccentric knee flexor strength and body mass ($r^2 = 0.08$) in this cohort. For the DTI analysis, eccentric knee flexor strength was scaled to body mass via the equation:

$$\text{Scaled Nordic Strength} = (\text{Nordic Force} / \text{Body Mass}^{0.54})$$

2.5 Power calculations

Power analysis was undertaken *post hoc* using G-Power (version 3.1.9) [18]. Using eccentric knee flexor strength data, power was calculated as 0.99 for the use of two-tailed independent t tests to compare groups (input parameters: effect size = 0.8; alpha = 0.05; sample size group 1 = 531; sample size group 2 = 74).

3.0 Results

3.1 Details of Cohort and Prospective HSIs

In total, 531 athletes (age, 23.4 ± 4.2 years; height, 184.8 ± 7.7 cm; body mass, 87.5 ± 12.4 kg, left peak force = 327 ± 93N, right peak force = 354 ± 92 N, mean peak force = 340 ± 92N and imbalance 20 ± 15%) had sufficient injury history and strength data and were included in this investigation (Figure 1). Athletes with a lifetime history of ACLR were a median of 48 months (interquartile range = 24-72 months) post injury at the time of testing.

Body mass had a significant effect on eccentric knee flexor strength ($r^2 = 0.08$; $p < 0.001$), where heavier athletes were stronger than lighter athletes. The eccentric knee flexor strength and between-limb imbalance for each group can be seen in Figure 2.

Athletes with a lifetime history of ACLR and HSI in the previous 12 months were significantly weaker (mean difference = -96N; 95% CI = -164 to -28N; p = 0.001; d = 1.23) and displayed larger between limb imbalances (mean difference = 21%; 95% CI = 10 to 33%; p < 0.001; d = 1.66) than uninjured players (those with neither ACLR nor recent HSI). There was no correlation ($r^2 = 0.01$; 95% CI = -0.02 to 0.02) between time since ACLR and the magnitude of eccentric knee flexor strength deficits. Athletes with a lifetime history of ACLR and no HSI in the previous 12 months were not weaker than those without a history of injury (mean difference = -15N; 95% CI = -50 to 18N; p = 0.646; d = 0.22), and the between limb imbalances of these two groups did not differ significantly (mean difference = 4%; 95% CI = -1 to 9%; p = 0.209; d = 0.41). Athletes who had at least one HSI in the previous 12 months were not weaker (mean difference = 23N; 95% CI = -1 to 49N; p = 0.080; d = 0.15) and did not display greater between limb imbalances (mean difference = -1%; 95% CI = -2 to 5%; p = 0.847; d = 0.03) than those with no history of injury in that time-frame.

INSERT FIGURE 2 HERE

Figure 2. Eccentric knee flexor strength (N) (bottom) and between-limb imbalance (%) (top) as measured during the Nordic hamstring exercise for each group. Eccentric knee flexor strength of the injured limb was used for athletes with a history of ACLR and HSI and the average of the left and right limbs was used for athletes with no previous injury. Force is reported in absolute terms (N). # - significantly different to all other groups (p < 0.001). * - significantly different to no previous injury (p < 0.05) and prior HSI (p < 0.05) in eccentric knee flexor strength.

Seventy-four athletes suffered at least one HSI during the subsequent competitive season (age, 24.6 ± 3.9 years; height, 183.6 ± 6.8 cm; body mass, 85.4 ± 11.7 kg), and 457 athletes did not (age, 23.2 ± 4.2 years; height, 185.0 ± 7.8 cm; body mass, 87.8 ± 12.5 kg). Subsequently injured athletes were significantly older than uninjured athletes (mean difference = 1.3 years; 95% CI = 0.3 to 2.3; p = 0.006; d = 0.34). No significant differences were observed for height (mean difference = 1.3 cm; 95% CI = -0.2 to 3.1; p = 0.114; d = 0.19) or body mass (mean difference = 2.4 kg; 95% CI = -0.5 to 5.3; p = 0.106;

d = 0.20) between the subsequently injured and uninjured athletes. Of the 74 athletes to suffer prospective hamstring injuries, 28 were AFL athletes, 20 were rugby players and 26 were soccer players.

3.2 Risk of future hamstring strain injury

3.2.1 Univariate and multivariable logistic regression

The univariate logistic regression showed that the biggest risk factors for future HSI were a recent history (12 months) of HSI (OR = 3.1; 95% CI = 1.8 to 5.4; $p < 0.001$) and a lifetime history of ACLR (OR = 2.2; 95% CI = 1.1 to 4.4; $p = 0.029$) (Table 1). Eccentric strength (OR = 1.0; 95% CI = 0.9 to 1.0; $p = 0.046$) and age (OR = 1.0; 95% CI = 1.0 to 1.1; $p = 0.010$) had extremely small but statistically significant effects on injury risk only according to the univariate analysis. The multivariable logistic regression revealed that a recent history (12 months) of HSI was the only significant risk factor for future HSI (OR = 2.9; 95% CI = 1.3 to 5.1; $p < 0.001$). A lifetime history of ACLR was not significant when eccentric strength was controlled for (OR = 1.8; 95% CI = 0.8 to 3.8; $p = 0.130$). Body mass and peak eccentric knee flexor strength had no significant effect on risk of future HSI once previous injury was controlled for (Table 2).

Table 1. Univariate logistic regression model

Risk factor	Odds ratio	95% CI	Significance	Parameter Estimates	Standard Error
Prior ACLR	2.2	1.1 to 4.4	p = 0.029	-0.399	0.173
Prior HSI	3.1	1.8 to 5.4	p < 0.001	-0.570	0.140
Body Mass (kg)	0.9	0.9 to 1.0	p = 0.114	-0.016	0.010
Age (Years)	1.0	1.0 to 1.1	p = 0.010	0.073	0.028
Eccentric Strength (N)[1]	1.0	0.9 to 1.0	p = 0.046	-0.003	0.001
Between-limb Imbalance(%)	2.6	0.5 to 13.7	p = 0.257	0.971	0.840

[1] Peak eccentric knee flexor strength (two-limb average)

CI, confidence interval; HSI, hamstring strain injury; ACLR, anterior cruciate ligament reconstruction

Table 2. Multivariable logistic regression model

Risk factor	Odds ratio	95% CI	Significance	Parameter Estimates	Standard Error
Prior ACLR	1.8	0.8 to 3.8	$p = 0.130$	-0.290	0.192
Prior HSI	2.9	1.6 to 5.1	$p < 0.001$	-0.535	0.144
Body Mass (kg)	0.9	0.9 to 1.0	$p = 0.253$	-0.013	0.011
Age (Years)	1.0	1.0 to 1.1	$p = 0.053$	0.058	0.029
Eccentric Strength (N)[1]	1.0	0.9 to 1.0	$p = 0.212$	-0.002	0.001
Between-limb Imbalance (%)	1.8	0.3 to 10.8	$p = 0.499$	0.616	0.903

[1] Peak eccentric knee flexor strength (two-limb average)

CI, confidence interval; HSI, hamstring strain injury; ACLR, anterior cruciate ligament reconstruction

3.2.2 Decision Tree Induction

The decision tree (Figure 3) was pruned back so that five splits remained. A HSI in the previous 12 months contributed the most to HSI risk (G^2 = 15.2) followed by a lifetime history of ACLR (G^2 = 14.8), while eccentric knee flexor strength featured to a smaller extent (G^2 = 4.8) by providing a protective effect for athletes with previous ACLR. Eccentric knee flexor strength allometrically scaled to body mass (Nordic Force / Body Mass$^{0.54}$) revealed that the probability of future HSI was higher for weaker athletes (Prob = 0.7 with eccentric strength < 26N.kg$^{-0.54}$; Prob = 0.2 with eccentric strength > 26N.kg$^{-0.54}$) with both prior ACLR and HSI in the previous 12 months. Athletes with a history of ACLR but no HSI in the previous 12 months who were weaker also had greater probability of future HSI than stronger athletes (Prob = 0.29 with eccentric strength <33N.kg$^{-0.54}$; Prob = 0.01 with eccentric strength > 33N.kg$^{-0.54}$).

INSERT FIGURE 3 HERE

Figure 3. The Decision Tree Induction (DTI) applied to those variables included in the final multiple logistic regression model. Eccentric knee flexor strength was scaled to body mass (Scaled Nordic Strength = Nordic Force / Body Mass$^{0.54}$) to remove the effect of body mass.

4.0 Discussion

The main goals of this study were to determine the effect of a prior ACLR, prior HSI, or both on the risk of future HSI, eccentric knee flexor strength and between-limb imbalance. Our main findings are that ACLR significantly increases the risk of subsequent HSI and that only a combination of prior ACLR and recent HSI (within 12 months) was associated with knee flexor weakness. Toohey and colleagues (2017) previously conducted a systematic review and meta-analysis which included two of the three studies that formed the current analysis, plus data from a third study [12]. They also reported that prior ACLR was associated with a heightened risk of future HSI [5], although their analysis did not take into account the possible effects of eccentric knee flexor strength. The inclusion of our third study [12] and consistent strength measures employed across all three studies [13, 11, 12] also allowed exploration of the role of eccentric strength in future HSI.

The factors that best explain high hamstring injury rates after ACLR are unknown, although proprioceptive [19] and strength deficits [20, 6, 7] and altered gait [21, 22] have been hypothesised to contribute. On the basis of the logistic regressions in this study, the impact of peak forces during the NHE on future hamstring injury risk was confounded by prior ACL injury. The decision tree analysis suggests the possibility that stronger athletes with a history of ACLR but no recent hamstring injury were less likely to experience hamstring strains than weaker ones. For example, none of 16 footballers with scaled Nordic strength $>33\text{N.kg}^{-0.54}$ sustained a HSI during follow-up while 8 of 27 weaker athletes did. A protective effect of high eccentric strength was also noted for ACLR recipients with a recent history of HSI, although the small number of players in this category limits confidence in the results. Future studies with a larger sample of athletes with previous ACLR may be able to determine, more definitively, the role of strength in protecting against HSI.

In the soccer cohort reported on here, short fascicles within the biceps femoris long head were associated with an increased risk of HSI [12]. Furthermore, athletes with previous ACLRs from semitendinosus grafts have been reported to exhibit ~15% deficits in biceps femoris long head fascicle lengths in their previously injured limbs [7]. However, we did not assess muscle architecture in either the AFL or rugby players so it is not possible to know if athletes with ACLR in the current study also had ipsilateral fascicle length deficits. Schuermans and colleagues [23] have reported that athletes with a relatively high reliance on biceps femoris and low use of semitendinosus during fatiguing knee flexor exercise, as determined by functional magnetic resonance imaging, have an elevated risk of HSI [24]. As semitendinosus grafts are very often employed in ACLR in Australian football players and this procedure is associated with chronic deficits in semitendinosus muscle volume and length [8, 25], and reduced medial hamstring activation [26], it seems reasonable to suggest that athletes would rely, after this surgery, significantly more on the biceps femoris and less on the semitendinosus while running. We have also shown that recreational athletes with a history of unilateral ACLR exhibit markedly reduced semitendinosus use in the surgical than control limbs (as determined by functional MRI) during the performance of the NHE [27]. Unfortunately, we do not have all the details of surgical graft type for the ACLR recipients in this study, so it is not possible to report what proportion of athletes had undergone semitendinosus, with or without gracilis grafts, as opposed to patellar tendon (or other) grafts. In the soccer cohort, however, 13 of the 16 ACLR's involved semitendinosus and, in our experience, this procedure is the standard in a significant majority (>80%) of AFL and rugby clubs in Australia. It seems reasonable to suggest, therefore, that semitendinosus grafts had been performed on a majority of the ACLR recipients in this study.

Deficits in knee flexor strength after ACLR have been noted in some [20, 6, 7], but not all previous studies [28, 29]. Persistent deficits in eccentric strength have also been reported after HSI [17]. In this study, no such deficits were observed in players who had experienced just one of these injuries. The discrepancies may be explained by the contraction mode of the knee flexor strength tests, the time since injury and surgical repair and the nature of the rehabilitation programs employed. A majority (428/531) of the athletes in this study were playing at the elite levels of their respective codes and it is likely that most rehabilitation programs were well supervised and that subsequent conditioning programs were multifaceted. Nevertheless, athletes with both a history of ACLR and a HSI within the previous 12 months were weaker and had larger between limb imbalance than those without a history of injury despite having returned to full training at the time of strength testing. These athletes may require more specific strength-oriented rehabilitation than they are currently getting in elite sport environments and the current decision tree analysis suggests that higher levels of eccentric strength may reduce the risk of subsequent HSI.

4.1 Limitations

It is important to acknowledge some limitations with the current study. The major one is the lack of information regarding the graft types for some of the athletes. This could not be overcome because the original studies were prospective risk factor investigations of hamstring injury and did not involve collection of this information from all participants. Furthermore, de-identification of athlete data prevented us from finding out about graft types retrospectively. Further information regarding graft type may have allowed a comparison of the effects of semitendinosus and patellar grafts on subsequent hamstring injury risk. Unfortunately, given the relatively small number of athletes with prior ACLR (n=53), we were underpowered to detect small to moderate effect sizes in this population. Another limitation of the study is related to strength measurements during the NHE. Results of this strength test are influenced to some degree by athlete body mass [30] and height (via altering the moment arm of the above-knee body segment), so any differences between injured and uninjured athletes in these parameters would potentially have impacted on the strength comparisons that were made. To minimise the effect of body mass, it was used as a covariate in the analysis of covariance and eccentric knee flexor strength was scaled to body mass for the decision tree analysis. Furthermore, body mass and height did not differ significantly between players who did and did not sustain a HSI during the period of observation, so any negative impacts were likely small. Another limitation is the incomplete nature of previous hamstring injury histories. Given the shortcomings in recall, we enquired about hamstring injuries only in the previous 12 month period and it is possible that a number of athletes classified as “uninjured” still had deficits of some sort in hamstring capacity as the result of older injuries. Finally, we did not have enough injuries to test the decision tree model with a hold-out dataset, so future work should assess the validity of the current findings.

5.0 Conclusion

A history of ACLR, like a history of HSI, is a predictor of future HSI. ACLR without recent HSI and HSI alone were not associated with deficits in eccentric strength, although those with a prior ACLR and a HSI within the last 12 months displayed relatively low levels of eccentric knee flexor strength and larger between limb imbalances than athletes without injury. Further work is required to determine whether higher levels of eccentric knee flexor strength may partially protect athletes with a history of ACLR against future HSI. Future work is needed to determine why a history of ACLR predisposes for future HSI in athletes and how this risk is best minimised.

Compliance with Ethical Standards

Funding

No sources of funding were used to assist in the preparation of this article.

Conflicts of Interest

AS is listed as a co-inventor on a patent filed for the knee-flexor testing device employed in this study (PCT/AU2012/001041.2012) as well as being a minority shareholder in the company responsible for comercialisng the device.

DO is listed as a co-inventor on a patent filed for a field-testing device of eccentric hamstring strength (PCT/AU2012/001041.2012) and is a minority shareholder in the company responsible for commercialising the device. Data from prototypes of this device is presented in the current manuscript. DO is also the Chair of the Vald Performance Research Committee, a role that is unpaid. DO has received funding from Vald Performance for research unrelated to the current manuscript. DO's brother and brother-in-law are employees of Vald Performance. DO's brother is a minority shareholder in Vald Performance Pty Ltd.

MB has previously received funding from VALD Performance for research unrelated to the current project.

MW is a member of the Vald Performance research advisory committee and has previously received travel and subsistence support from VALD Performance for research unrelated to the current project.

Author Contributions

DM was involved in the study design, data reanalysis and manuscript write up. AS was involved in study design and manuscript write up. DO, MB and RT were principal investigators in the three original studies for which AS, DO, RT and MB were involved with recruitment and testing. DO, MB, RT and MW were involved with the study design, analysis and preparation of this manuscript. All authors had full access to the data in this study and are responsible for the integrity and accuracy of the data analysis.

Transparency Declaration

The lead author* (DM) affirms that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained. * = The manuscript's guarantor.

Ethical Clearance

All participants provided written, informed consent for this study, which was approved by the Queensland University of Technology Human Research Ethics Committee and the Australian Catholic University Human Research Ethics Committee. **All previous studies were performed in accordance with the standards of ethics outlined in the Declaration of Helsinki.**

Patient and Public Involvement

Patients or the public were not involved in the design, or conduct, or reporting, or dissemination plans of our research.

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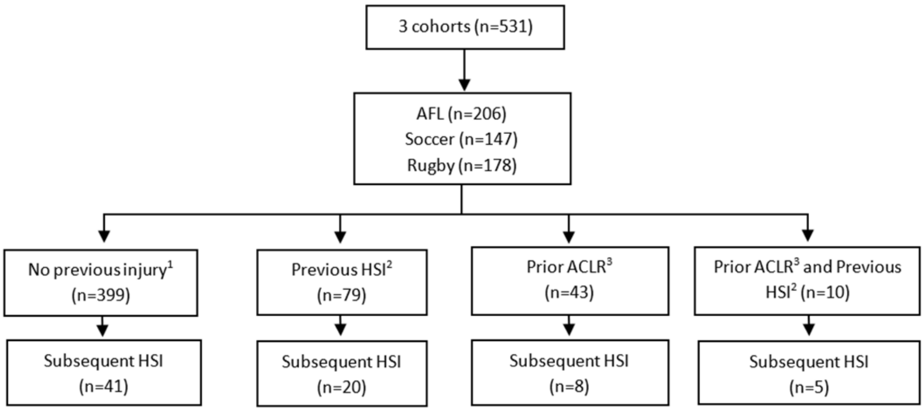
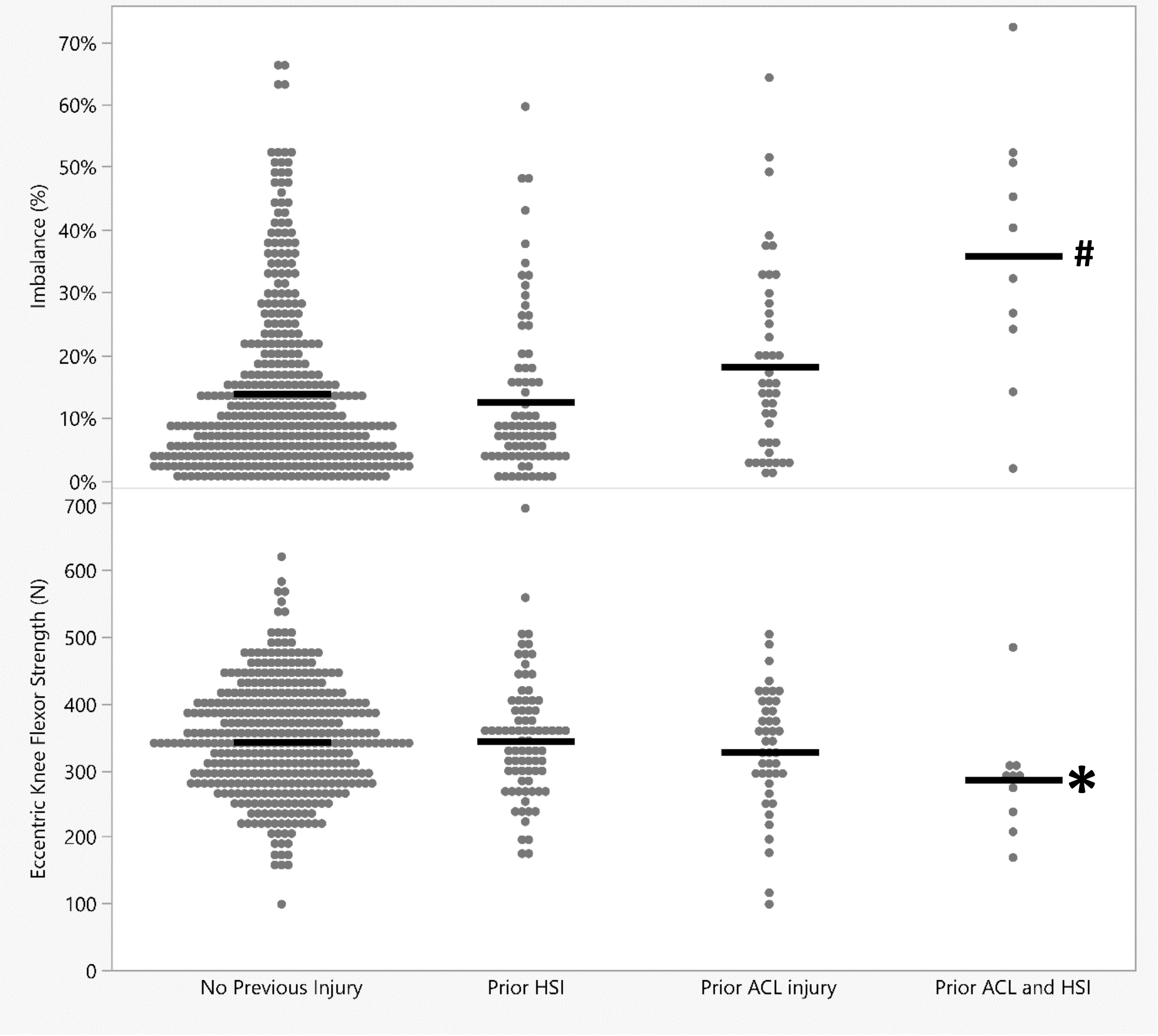
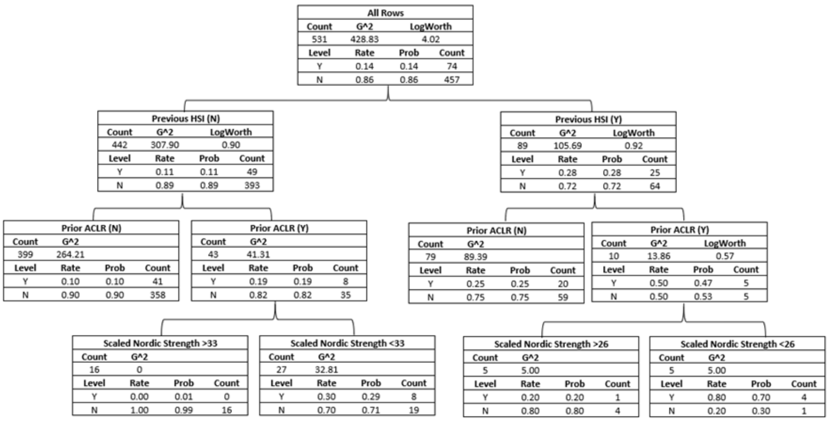

3 cohorts (n=531)
AFL (n=206)
Soccer (n=147)
Rugby (n=178)
No previous injury[1] (n=399)
Previous HSI[2] (n=79)
Prior ACLR[3] (n=43)
Prior ACLR[3] and Previous HSI[2] (n=10)
Subsequent HSI (n=41)
Subsequent HSI (n=20)
Subsequent HSI (n=8)
Subsequent HSI (n=5)


Imbalance (%)
70%
60%
50%
40%
30%
20%
10%
0%
#
Eccentric Knee Flexor Strength (N)
700
600
500
400
300
200
100
0
*
No Previous Injury
Prior HSI
Prior ACL injury
Prior ACL and HSI



All Rows

Count	**G^2**	**LogWorth**	
531	428.83	4.02	
Level	**Rate**	**Prob**	**Count**
Y	0.14	0.14	74
N	0.86	0.86	457

Previous HSI (N)

Count	**G^2**	**LogWorth**	
442	307.90	0.90	
Level	**Rate**	**Prob**	**Count**
Y	0.11	0.11	49
N	0.89	0.89	393

Previous HSI (Y)

Count	**G^2**	**LogWorth**	
89	105.69	0.92	
Level	**Rate**	**Prob**	**Count**
Y	0.28	0.28	25
N	0.72	0.72	64

Prior ACLR (N)

Count	**G^2**		
399	264.21		
Level	**Rate**	**Prob**	**Count**
Y	0.10	0.10	41
N	0.90	0.90	358

Prior ACLR (Y)

Count	**G^2**		
43	41.31		
Level	**Rate**	**Prob**	**Count**
Y	0.19	0.19	8
N	0.82	0.82	35

Prior ACLR (N)

Count	**G^2**		
79	89.39		
Level	**Rate**	**Prob**	**Count**
Y	0.25	0.25	20
N	0.75	0.75	59

Prior ACLR (Y)

Count	**G^2**	**LogWorth**	
10	13.86	0.57	
Level	**Rate**	**Prob**	**Count**
Y	0.50	0.47	5
N	0.50	0.53	5

Scaled Nordic Strength >33

Count	**G^2**		
16	0		
Level	**Rate**	**Prob**	**Count**
Y	0.00	0.01	0
N	1.00	0.99	16

Scaled Nordic Strength <33

Count	**G^2**		
27	32.81		
Level	**Rate**	**Prob**	**Count**
Y	0.30	0.29	8
N	0.70	0.71	19

Scaled Nordic Strength >26

Count	**G^2**		
5	5.00		
Level	**Rate**	**Prob**	**Count**
Y	0.20	0.20	1
N	0.80	0.80	4

Scaled Nordic Strength <26

Count	**G^2**		
5	5.00		
Level	**Rate**	**Prob**	**Count**
Y	0.80	0.70	4
N	0.20	0.30	1

Term	Number of Splits	G^2
Previous HSI	**1**	**15.2**
Prior ACLR	**2**	**14.8**
Scaled Nordic Strength	**3**	**4.8**