Screening Hamstring Injury Risk Factors Multiple Times in a Season Does Not Improve the Identification of Future Injury Risk

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ABSTRACT

OPAR, D. A., J. D. RUDDY, M. D. WILLIAMS, N. MANIAR, J. T. HICKEY, M. N. BOURNE, T. PIZZARI, and R. G. TIMMINS. Screening Hamstring Injury Risk Factors Multiple Times in a Season Does Not Improve the Identification of Future Injury Risk. *Med. Sci. Sports Exerc.*, Vol. 54, No. 2, pp. 321–329, 2022. **Purpose:** To determine if eccentric knee flexor strength and biceps femoris long head (BFlh) fascicle length were associated with prospective hamstring strain injury (HSI) in professional Australian Football players, and if more frequent assessments of these variables altered the association with injury risk. **Methods:** Across two competitive seasons, 311 Australian Football players (455 player seasons) had their eccentric knee flexor strength during the Nordic hamstring exercise and BFlh architecture assessed at the start and end of preseason and in the middle of the competitive season. Player age and injury history were also collected in preseason. Prospective HSIs were recorded by team medical staff. **Results:** Seventy-four player seasons (16%) sustained an index HSI. Shorter BFlh fascicles (<10.42 cm) increased HSI risk when assessed at multiple time points only (relative risk [RR], 1.9; 95% confidence interval [CI], 1.2–3.0). Neither absolute (N) nor relative ($N \cdot kg^{-1}$) eccentric knee flexor strength was associated with HSI risk, regardless of measurement frequency (RR range, 1.0–1.1); however, between-limb imbalance (>9%), when measured at multiple time points, was (RR, 1.8; 95% CI, 1.1–3.1). Prior HSI had the strongest univariable association with prospective HSI (RR, 2.9; 95% CI, 1.9–4.3). Multivariable logistic regression models identified a combination of prior HSI, BFlh architectural variables and between-limb imbalance in eccentric knee flexor strength as optimal input variables; however, their predictive performance did not improve with increased measurement frequency (area under the curve, 0.681–0.726). **Conclusions:** More frequent measures of eccentric knee flexor strength and BFlh architecture across a season did not improve the ability to identify which players would sustain an HSI. **Key Words:** AUSTRALIAN FOOTBALL, HAMSTRING MUSCLES, WOUNDS AND INJURIES, RISK FACTORS, PROSPECTIVE STUDY

Hamstring strain injuries (HSIs) are the most common injury in Australian Football (1), with a reinjury rate ranging between approximately 10% and 25% (1,2). Consequently, substantial effort has gone into identifying injury risk factors (3), but few studies have considered how their association with injury may change over a season.

The strongest risk factors for HSI are older age and a prior HSI (3), both nonmodifiable factors. Recent work has focused on identifying modifiable risk factors that can be targeted via interventions. For example, elite Australian Football players with low levels of eccentric knee flexor strength during the Nordic hamstring exercise (NHE) were 2.7 times more likely to sustain an HSI than their stronger counterparts (4). Interactions were also observed between strength, prior injury and age, whereby higher levels of eccentric knee flexor strength ameliorated the risk of injury associated with older age or prior HSI. Although eccentric knee flexor strength may be associated with HSI at a cohort level, it has displayed poor predictive performance in Australian Football (5).

Biceps femoris long head (BFlh) fascicle length (6) is also a modifiable risk factor for HSI. In soccer players, shorter BFlh fascicles (<10.56 cm) increased HSI risk by 4.1 times

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compared with longer BFlh fascicles (≥10.56 cm) (6). Longer BFlh fascicles also reduced the risk associated with being older or having a prior HSI. Although Australian Football players with a prior HSI display shorter fascicles than those without (7), no study has examined whether BFlh fascicle length is a risk factor for HSI in Australian Football.

A limitation of many prospective studies is that associations with injury risk are made from measures taken at a single time point (e.g., preseason), whereas the injuries occur in the subsequent months/years (3). Eccentric knee flexor strength (8) and BFlh fascicle lengths (7) both change across preseason, suggesting a need to account for fluctuations in modifiable risk factors.

The aim of this study was to determine if eccentric knee flexor strength and BFlh fascicle length were associated with prospective HSI in professional Australian Football players and if measuring these variables more frequently throughout the season altered the association with injury risk.

METHODS

Study design and participants. This prospective cohort study was conducted over the 2018 (November 2017 to August 2018) and 2019 (November 2018 to August 2019) Australian Football League (AFL) regular seasons (i.e., not including finals) and involved six teams. The study was approved by the Australian Catholic University Human Research Ethics Committee (approval number 2017-208H) and each player provided written informed consent before participation in each season.

At the start of preseason team medical staff provided details of each player's history of HSI in the prior season (i.e., prior 12 months), and whether they had ever suffered an anterior cruciate ligament (ACL) injury. Subsequently, players underwent assessments of eccentric knee flexor strength and BFlh fascicle length at three time points: start of preseason (November/December), end of preseason (February/March), and middle of the competitive season (May/June). The exact dates for testing varied slightly between teams because of scheduling constraints. For any player who sustained an HSI during the study period, the team medical staff provided a standardized injury report form.

Eccentric knee flexor strength. The assessment of eccentric knee flexor strength during the NHE has been reported previously (4,6,9,10). Players knelt on an instrumented device (NordBord, Vald Performance, Queensland, Australia), with their ankles secured immediately superior to the lateral malleolus by individual ankle hooks attached to uniaxial load cells. All players completing this testing were familiar with the NHE. Players were instructed to gradually lean forward while maximally resisting this movement with both limbs by performing a forceful eccentric contraction of their knee flexors. Throughout the exercise, athletes held their trunk and hips in a neutral position and their hands across the chest. After a self-selected warm-up, players performed a single set of one to three maximal repetitions of the NHE, dictated by the practices of each team. Eccentric knee flexor strength was determined for each leg as the highest peak force produced during the testing set in absolute (N) and scaled relative to body mass ($\mathrm{N{\cdot}kg^{-1}}$). Between-limb imbalance was calculated as:

$$((\mathrm{Limb_{max}} - \mathrm{Limb_{min}})/\mathrm{Limb_{max}}) \times 100$$

where $\mathrm{Limb_{min}}$ is the eccentric knee flexor force (N) of the weaker limb and $\mathrm{Limb_{max}}$, the eccentric knee flexor force (N) of the stronger limb.

Biceps femoris long head architecture. The methods to assess BFlh architecture have been previously reported (7,11–13). Briefly, muscle thickness, pennation angle, and fascicle length of the BFlh were determined from ultrasound images taken along the longitudinal axis of the muscle belly utilizing a two-dimensional, B-mode ultrasound (frequency, 12 MHz; depth, 8 cm; field of view, 14 × 47 mm) (GE Healthcare Vivid-i, Wauwatosa, WI). The scanning site was determined as the halfway point between the ischial tuberosity and the knee joint fold, along the line of the BFlh. All architectural assessments were performed with the participant prone on a massage plinth, after 5 min of inactivity. The orientation of the probe was then manipulated by the assessor (R.G.T.), who has published reliability for assessing BFlh fascicle length with intraclass correlations >0.90 (14).

Once the images were collected, analysis was undertaken off-line (MicroDicom, Version 0.7.8, Bulgaria). Muscle thickness was defined as the distance between the superficial and intermediate aponeuroses of the BFlh. Pennation angle was defined as the angle between the intermediate aponeurosis and a fascicle of interest. The aponeurosis angle for both aponeuroses was determined as the angle between the line marked as the aponeurosis and an intersecting horizontal reference line across the captured image (15). As the entire fascicle was not visible in the field of view of the probe, its length was estimated via the following equation (15):

$$\mathrm{FL} = \sin(\mathrm{AA} + 90^\circ) \times \mathrm{MT}/\sin(180^\circ - (\mathrm{AA} + 180^\circ - \mathrm{PA}))$$

where FL is fascicle length; AA, aponeurosis angle; MT, muscle thickness; and PA, pennation angle. Fascicle length was reported in absolute (cm) and relative to muscle thickness (derived from the quotient of BFlh fascicle length and BFlh muscle thickness). Although BFlh fascicle length relative to muscle thickness has not previously been reported as a factor associated with prospective HSI, it is a variable that is lesser in previously injured BFlh compared with contralateral limbs (14). The extrapolation measure and equation has been validated against cadaveric BFlh tissue and as such is considered a robust way of estimating fascicle lengths (15). The same assessor (R.G.T.) collected all scans and performed all analyses offline. During analysis, the assessor was blinded to participant identifiers.

Prospective hamstring strain injury reporting. An HSI was defined as pain in the posterior thigh that caused cessation of subsequent exercise, confirmed by physical examination by the team physiotherapist or doctor (16,17). For all HSIs, team medical staff completed a standard injury report form that requested details on the injured limb, injured muscle, activity type performed at time of injury, and the number of days taken to return to full participation in training and matches. The first instance of an HSI within a season was recorded as an index injury. A recurrent HSI was defined as another HSI within the same season that occurred in the same leg and same muscle as the index injury. A subsequent HSI was defined as another HSI within the same season but did not have to occur in the same leg or muscle as the index injury.

Statistical analysis. Statistical analyses were performed using the R statistical programming language (18) and the following packages: dplyr, OptimalCutpoints, epitools, and pROC, unless otherwise stated.

Demographic data (age, stature, mass, and AFL games experience) were compared between the injured and uninjured groups using a two-tailed independent t test, with significance set at $P < 0.05$ using JMP Pro 14.2.0 (SAS Institute, Inc., Cary, NC).

To address the research aim, the data were analyzed in two ways. The first analysis utilized all risk factor data assessed at the start of preseason only. The second analysis utilized nonmodifiable risk factor data (e.g., age, prior HSI, prior ACL injury) assessed at the start of preseason and modifiable risk factor data (BFlh architecture, eccentric knee flexor strength) assessed at multiple time points. For the second analysis, prospective HSIs were determined as injuries occurring within three blocks based on the timing of risk factor data assessments (between start of preseason and end of preseason; between the end of preseason and the middle of in-season and; between the middle of in-season and the end of the in-season before the commencement of finals). Athletes who sustained a prospective HSI during either the first or second assessment block were censored from subsequent assessment windows within that season. Data in each of the three blocks were included as independent data points.

Optimal cut points (maximizing the difference between sensitivity and 1-specificity) for continuous variables were determined using receiver operating characteristic curves. These cut points were then used to determine univariable relative risks (RR), 95% confidence intervals (95% CI), sensitivity and specificity, and the area under the curve (AUC). For dichotomous variables (prior HSI and ACL injury), RR, 95% CI, sensitivity, and specificity was determined by comparing those with and without a history of injury and occurrence of prospective HSI. The univariable cut points for eccentric knee flexor strength and BFlh fascicle length were used to categorize each data point into one of four quadrants (long and strong, long and weak, short and strong, short and weak). The strong and long quadrant was used as the reference group, with the RR, 95% CI, sensitivity, and specificity calculated for the three other groups. An RR was considered significant when the 95% CI did not cross 1.00.

Following the univariable analyses, multivariable logistic regression models were built. The variables included in these models were determined *a priori* according to previous research (6). An additional mixed stepwise regression model was used to establish an optimal model. Before running the stepwise regression analysis, correlation analyses were performed to identify redundant predictor variables. A Pearson's correlation coefficient threshold of >0.70 was applied. If the pairwise correlation between two variables was >0.70, the variable with the larger mean pairwise correlation (across all variables) was discarded, with the mean pairwise correlations being reevaluated after the removal of every variable. The correlation matrices for all variables collected at both a single time point and multiple time points can be found in Supplemental Digital Content 1 (see Table, Supplemental Digital Content 1, correlation matrices for all variables, http://links.lww.com/MSS/C422). Following the correlation analyses, the stepwise regression analyses were performed using the remaining variables. The optimal model was built using the subset of variables that minimized the model's Akaike information criterion. To assess the performance of each model, the AUC and associated 95% CI were determined. To compare model performance across the different measurement frequencies (e.g., performance of model 1 at the single time point vs the multiple time point were compared) the 95% CI were assessed (using 5000 iterations of stratified bootstrap sampling), and if there was no overlap between the 95% CI, then model performance was considered different. If there was overlap between the 95% CI model performance was considered not to be different.

RESULTS

Cohort and Prospective Injury Details

Three-hundred and eleven male Australian Football players, amounting to 455 player seasons (23.7 ± 3.8 yr, 188.1 ± 7.6 cm, 86.5 ± 8.8 kg) were assessed on at least one occasion. Of those player seasons, 381 (83.7%) did not sustain an HSI and 74 (16.3%) did (Table 1).

Of the 74 index HSIs (37 each in the left and right legs), the primary mechanism of injury was high-speed running (46%) followed by acceleration/deceleration (15%) and jumping or tackling (12%). Of the 74 index HSIs, 66% had details on the muscle injured. Of these available data, 82% of index HSI were in the BFlh, 14% were in the semimembranosus, and 4% were in the semitendinosus.

Thirteen (18%) and 9 (12%) of the 74 index HSIs went on to sustain a subsequent and recurrent HSI, respectively. The

TABLE 1. Demographic and prior injury data from 455 Australian Football player seasons which subsequently resulted in a prospective HSI or did not.

	Injured (n = 74)	Uninjured (n = 381)	P
Age, yr	24.0 ± 4.0	23.6 ± 3.8	0.502
Stature, cm	187.3 ± 7.0	188.3 ± 7.8	0.286
Mass, kg	86.4 ± 8.4	86.5 ± 8.9	0.920
AFL games experience, n	64 ± 77	63 ± 72	0.913
Position, n (%)			
Defender	26 (35)	117 (31)	
Midfielder	21 (28)	130 (34)	
Forward	25 (34)	104 (27)	
Ruck	2 (3)	30 (8)	
Prior HSI, n (%)			
Yes	23 (31)	40 (11)	
No	51 (69)	341 (89)	
Prior ACL injury, n (%)			
Yes	4 (5)	26 (7)	
No	70 (95)	355 (93)	

median time taken to return to full training was 15 d (IQR, 12 d) for the 88% of cases of index HSI where such data were available. Of the 74 index HSI, 57% were sustained during the in-season period with the median time to return to play being 21 d (IQR, 18 d). One player sustained a recurrent injury during rehabilitation.

The median number of days between preseason BFlh architectural and eccentric knee flexor strength assessments and the subsequent occurrence of an index HSI was 144 d (IQR, 102 d) and 136 d (IQR, 115 d), whereas for measures taken at multiple time points, the corresponding values were 53 d (IQR, 39 d) and 51 d (IQR, 48 d), respectively.

Univariable Analysis

A breakdown of the number of player seasons included for each of the univariable analyses can be found in Supplemental Digital Content 2 (see Table, Supplemental Digital Content 2, breakdown of the total number of Australian Football player seasons included for each of the univariable analyses, http://links.lww.com/MSS/C423).

Demographic and injury history risk factors. A prior HSI was associated with greater risk of a future HSI (RR, 2.85; 95% CI, 1.88–4.33; Fig. 1). All demographic data and prior ACL injury were not significantly associated with future HSI risk (RR range, 0.80–1.18; Fig. 1).

BFlh architectural and eccentric knee flexor strength risk factors. When assessed at the start of preseason, lesser relative fascicle length (≤3.82; RR, 1.78; 95% CI, 1.15–2.75) and larger pennation angle (>15.8°; RR, 1.78; 95% CI, 1.16–2.74) were associated with greater HSI risk (Fig. 2). When compared with the strong and long quadrant, none of the other BFlh fascicle length and eccentric knee flexor strength quadrants had an elevated RR (RR range, 1.32–1.70; Table 2, Fig. 3).

When assessed at multiple time points, lesser relative fascicle length maintained a consistent association with prospective HSI risk (≤3.87; RR, 1.68; 95% CI, 1.06–2.65; Fig. 2), whereas pennation angle did not (>15.6°; RR, 1.52; 95% CI, 0.97–2.39; Fig. 2). Absolute fascicle length (≤10.42 cm; RR, 1.89; 95% CI, 1.20–2.99; Fig. 2) and eccentric knee flexor strength imbalance (>9%; RR, 1.81; 95% CI, 1.06–3.08; Fig. 2) showed significant associations with prospective HSI risk when measured at multiple time points. When compared with the long and strong quadrant, only the short and strong quadrant (RR, 2.60; 95% CI, 1.20–5.65) had an elevated RR (Table 2, Fig. 3).

Multivariable Logistic Regression

None of the *a priori* multivariable models were statistically significant, regardless of the measurement frequency (see Table, Supplemental Digital Content 3, Multivariate logistic regression model outputs and receiver operator characteristic curve data, http://links.lww.com/MSS/C424). For measures taken at the start of preseason, the final predictors from the stepwise regression included in the optimal model (AUC, 0.681; 95% CI, 0.605–0.755) were prior HSI and relative fascicle length (Supplemental Digital Content 3, http://links.lww.com/MSS/C424, Fig. 4). For measures taken at multiple time points, the final predictors from the stepwise regression included in the optimal model (AUC, 0.726; 95% CI, 0.651–0.794) were prior HSI, relative fascicle length and between-limb imbalance in eccentric knee flexor strength (Supplemental Digital Content 3, http://links.lww.com/MSS/C424, Fig. 5; see Figure, Supplemental Digital Content 4, multivariate logistic regression of prospective HSI probability and factors assessed at multiple time points, http://links.lww.com/MSS/C425). Comparison of the AUC and 95% CI for each model at the two different measurement frequencies can be found in Figure 6. The 95% CI for the AUC for all models overlapped when comparing the single time point against the multiple time point measures.

DISCUSSION

This is, to the best of our knowledge, the first study to assess whether more frequent measures of HSI risk factors improves their association with prospective HSI. Multivariable logistic regression using HSI risk factors collected at a single or multiple time points did not show superior predictive performance with greater testing frequency. This finding questions whether it is necessary to measure eccentric knee flexor strength and BFlh architecture more frequently than a single time point, if the goal of such testing is to ascertain future HSI risk.

Variable	Cutpoint	Relative risk 95% CI			AUC	Sensitivity	Specificity
		Estimate	Lower	Upper			
Height	≤ 186cm	1.18	0.78	1.79	0.53	0.50	0.55
Mass	≤ 85kg	1.12	0.74	1.71	0.51	0.53	0.51
Age	> 23.4years	1.15	0.76	1.74	0.52	0.51	0.53
Games played	≤ 35	1.09	0.71	1.66	0.50	0.51	0.52
Prior HSI	Yes	2.85	1.88	4.33		0.32	0.90
Prior ACL injury	Yes	0.80	0.31	2.04		0.06	0.93

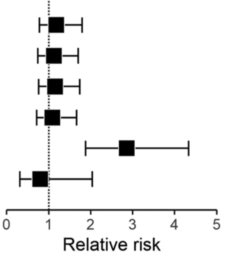
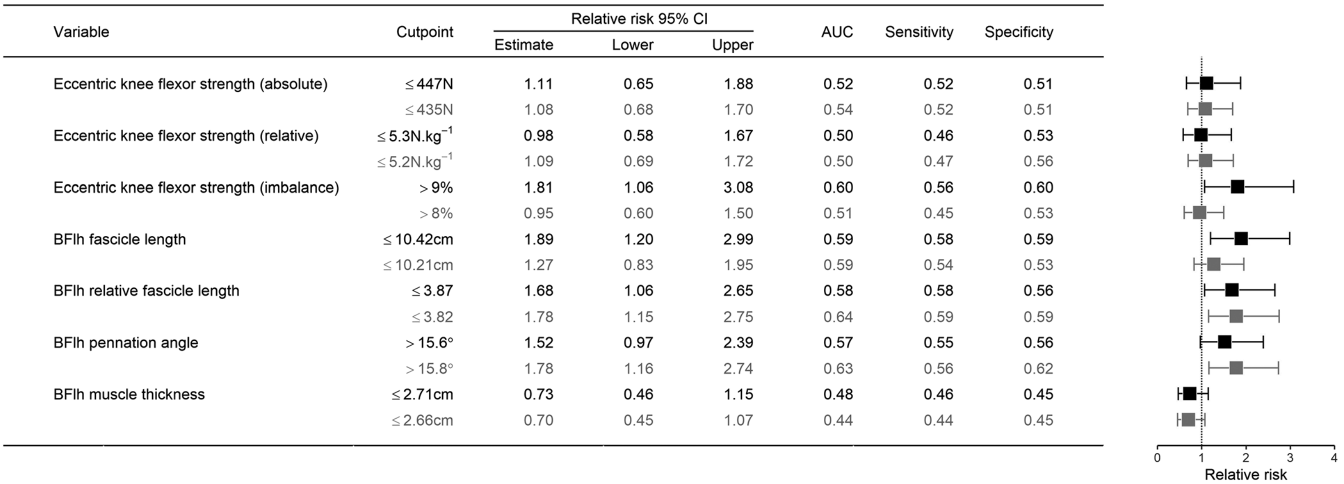


FIGURE 1—Relative risk and 95% confidence intervals (95% CI) of demographic and injury history risk factors for prospective HSI assessed at the start of preseason for a cohort of 455 Australian Football player seasons. The at-risk group for these comparisons is defined by the cut point. Cut points for continuous variables were determined via receiver operator characteristic curve analysis.



Variable	Cutpoint	Relative risk 95% CI			AUC	Sensitivity	Specificity
		Estimate	Lower	Upper			
Eccentric knee flexor strength (absolute)	≤ 447N	1.11	0.65	1.88	0.52	0.52	0.51
	≤ 435N	1.08	0.68	1.70	0.54	0.52	0.51
Eccentric knee flexor strength (relative)	≤ 5.3N.kg^{-1}	0.98	0.58	1.67	0.50	0.46	0.53
	≤ 5.2N.kg^{-1}	1.09	0.69	1.72	0.50	0.47	0.56
Eccentric knee flexor strength (imbalance)	> 9%	1.81	1.06	3.08	0.60	0.56	0.60
	> 8%	0.95	0.60	1.50	0.51	0.45	0.53
BFlh fascicle length	≤ 10.42cm	1.89	1.20	2.99	0.59	0.58	0.59
	≤ 10.21cm	1.27	0.83	1.95	0.59	0.54	0.53
BFlh relative fascicle length	≤ 3.87	1.68	1.06	2.65	0.58	0.58	0.56
	≤ 3.82	1.78	1.15	2.75	0.64	0.59	0.59
BFlh pennation angle	> 15.6°	1.52	0.97	2.39	0.57	0.55	0.56
	> 15.8°	1.78	1.16	2.74	0.63	0.56	0.62
BFlh muscle thickness	≤ 2.71cm	0.73	0.46	1.15	0.48	0.46	0.45
	≤ 2.66cm	0.70	0.45	1.07	0.44	0.44	0.45

FIGURE 2—Relative risk and 95% CI of eccentric knee flexor strength and BFlh architectural risk factors for prospective hamstring strain injury assessed at a single time point (gray; start of preseason) or multiple time points (black; start of preseason, end of preseason, middle of in-season) for a cohort of 455 Australian Football player seasons. The at-risk group for these comparisons is defined by the cut point. Cut points for continuous variables were determined via receiver operator characteristic curve analysis.

BFlh architecture and HSI risk. Our findings partially support prior work in soccer players demonstrating that shorter BFlh fascicles increased the risk of future HSI (6), although our highest relative risk (RR = 1.9) did not reach the levels reported in soccer players (RR = 4.1 (6)). This discrepancy might be explained by our larger sample size (74 HSIs in 455 player seasons compared with 27 HSIs in 152 player seasons) (6), and may be a better reflection of the true effect. The difference could also be a consequence of the different physical demands of the respective sports. Testing at multiple time points may also be a better reflection of the association with HSI risk, because BFlh fascicle lengths change over the course of a season (7).

The mechanism by which either absolute or relative BFlh fascicle length may influence HSI risk is not fully understood. It has been proposed that athletes with longer BFlh fascicles may be less susceptible to muscle damage during forceful eccentric actions (19,20), such as during the terminal-swing phase of sprinting (21). Significant increases in BFlh fascicle length have been reported after 4- to 10-wk interventions using eccentrically biased hamstring exercise (19,22,23), which may be a key mechanism by which eccentric exercise provides protection against future HSI or reinjury (24); however, this is yet to be elucidated.

Eccentric knee flexor strength and HSI risk. Eccentric knee flexor strength and between-limb imbalance at the start of preseason were not associated with an increased risk of future HSI. Earlier work (4) reported that elite Australian Football players with lower levels of eccentric knee flexor strength (<256 N) during the NHE at the start of preseason, were 2.7 times more likely to suffer an HSI than their stronger counterparts. The findings of our study and another in Australian football (5) have failed to replicate the associations between eccentric knee flexor strength during the NHE and prospective HSI risk. Further, a recent meta-analysis (25) reported no significant association between preseason measures of eccentric knee flexor strength during the NHE and future HSI risk.

When assessed at multiple time points between-limb imbalance >9% was associated with future HSI. Previous work in elite Australian Football players reported no association between early or late preseason measures of between-limb imbalance in eccentric knee flexor strength and subsequent HSI (4,5). It is conceivable that between-limb imbalances in eccentric knee flexor strength might contribute to an elevated risk of HSI via alterations to running kinematics (26), or through an impaired ability to absorb energy during active lengthening (27), although this remains speculative. When interpreting the between-limb imbalance in eccentric knee flexor strength during the NHE the reader should keep in mind the percentage typical error (6.0%) and the minimal detectable change (0.17; when imbalance is expressed as a ratio) of the test (10).

Collectively, these data indicate that the true effect of eccentric knee flexor strength and/or imbalance on future risk of

TABLE 2. The univariable relative risk for future hamstring strain injury in Australian Football player seasons categorized into quadrants based on their eccentric knee flexor strength ("weak" or "strong") and biceps femoris long head (BFlh) fascicle length ("short" or "long").

Measurement Frequency	Reference Group	Risk Group	Relative risk 95% CI			Sensitivity	Specificity
			Estimate	Lower	Upper		
Single time point	Long & strong	Short & strong	1.70	0.87	3.31	0.60	0.56
		Short & weak	1.32	0.65	2.69	0.54	0.54
		Long & weak	1.48	0.75	2.92	0.59	0.53
Multiple time points	Long & strong	Short & strong	2.60	1.20	5.65	0.60	0.65
		Short & weak	2.06	0.93	4.53	0.58	0.60
		Long & weak	1.40	0.61	3.17	0.55	0.54

For measures taken at a single time point, weak eccentric knee flexor strength was considered as ≤435 N and short BFlh fascicle length was considered as ≤10.21 cm. For measures taken at multiple time points, weak eccentric knee flexor strength was considered as ≤447 N and short BFlh fascicle length was considered as ≤10.42 cm.

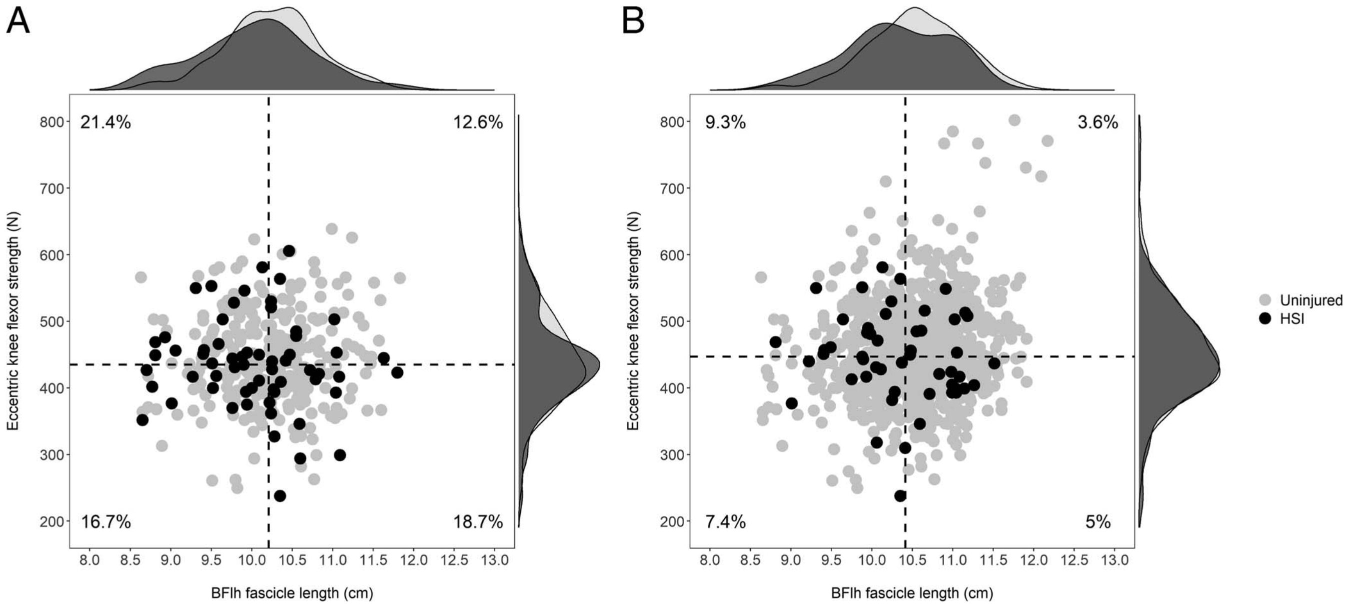


FIGURE 3—Scatter plot displaying the eccentric knee flexor strength and BFlh fascicle length in Australian Football players who did (*black circles*) and did not (*grey circles*) sustain a prospective HSI. Panel A represents data collected at only one time point (start of preseason) whereas panel B represents data collected at multiple time points (start of preseason, end of preseason, middle of in-season) across the season. The horizontal and vertical dashed lines represent the univariable cut points for each variable determined via receiver operator characteristic curve analysis, which subsequently allowed each data point to be categorized into quadrants (top left, short and strong; top right, long and strong; bottom left, short and weak; bottom right, long and weak). The value in each corner represents the rate of HSI in each quadrant as a percentage of the total data points in that quadrant. The plots on the top and right hand side of each graph are density plots of the injured and uninjured groups, respectively.

HSI, when assessed via the NHE, is at best small (3). This questions the practical utility of knee flexor strength measures for HSI risk identification purposes.

Nonmodifiable risk factors for HSI. Prior HSI was the only nonmodifiable factor significantly associated with future HSI. This is consistent with a recent meta-analysis, where prior HSI increased the risk of sustaining a future HSI 2.7-fold (3). Although the mechanisms by which prior HSI predisposes to future injury remain to be fully elucidated, it has been hypothesized that moderate to severe HSI may result in chronic neuromuscular inhibition of the injured muscle, which may contribute to negative downstream effects on structure, function and subsequent reinjury risk (28). Older age is another commonly cited risk factor for HSI, but the current study did not observe any association between age and future HSI. A large-scale analysis of 1932 HSI recorded across approximately 23 AFL seasons also observed no effect of greater age once prior HSI was accounted for (2).

Multivariable analyses. For measures taken at the start of preseason, longer relative BFlh fascicles reduced the probability of future HSI, and limited the increased risk associated with having a prior HSI (Fig. 4). Earlier work in elite soccer

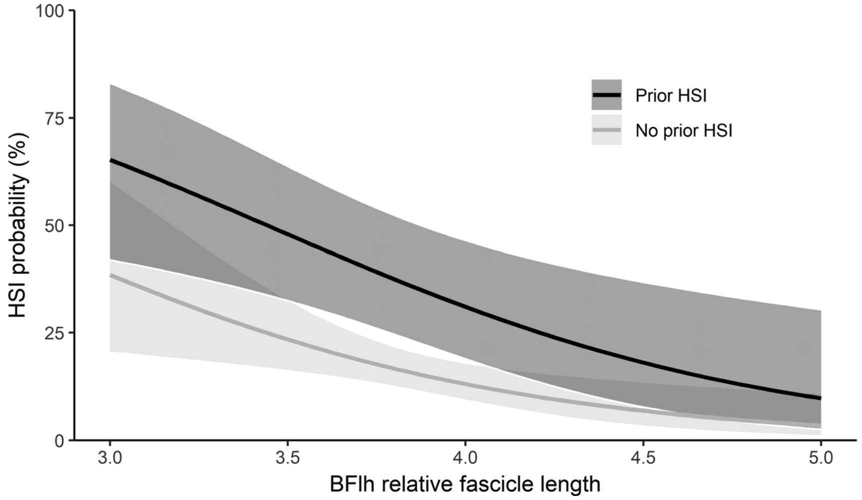


FIGURE 4—Multivariate logistic regression of prospective HSI probability and factors assessed at a single time point (start of preseason) for a cohort of 455 Australian Football player seasons. Predictor variables for the final multivariate model (AUC = 0.681) were determined using stepwise regression. The variables visualized above included prior HSI in the previous 12 months (*P* = 0.002) and BFlh relative fascicle length (*P* = 0.005).

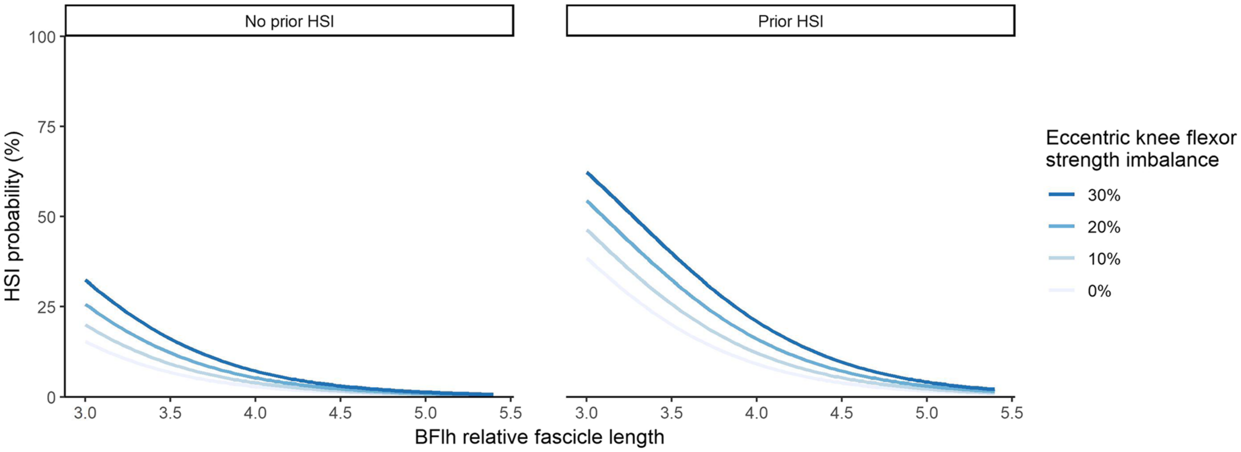


FIGURE 5—Multivariate logistic regression of prospective HSI probability and factors assessed at multiple time points (start of preseason, end of preseason, mid-season) for a cohort of 455 Australian Football player seasons. Predictor variables for the final multivariate model (AUC = 0.726) were determined using stepwise regression. These variables were prior HSI in the previous 12 months ($P < 0.001$), BFlh relative fascicle length ($P < 0.001$) and eccentric knee flexor strength imbalance ($P = 0.022$).

players revealed a similar relationship between BFlh fascicle length and prior injury, whereby longer fascicles reduced the risk of future HSI associated with a prior HSI. Larger BFlh muscles, with shorter fascicles and (presumably) fewer sarcomeres in series, may expose each individual sarcomere to higher levels of strain than smaller muscles with comparative fascicle lengths (29), particularly if coupled with a smaller BFlh aponeurosis width (30). The implications of larger muscles with, presumably, greater force generating capacity and the interaction with other musculotendinous morphological and architectural properties is still an area that requires further work.

When tested at multiple time points, relative BFlh fascicle length was inversely associated with the probability of HSI, particularly in previously hamstring strain injured athletes and those with between-limb imbalances in eccentric knee flexor strength (Fig. 5). A previous study observed a similar relationship between eccentric knee flexor strength imbalances and prior HSI, whereby the probability of HSI was augmented in rugby players with a history of HSI and larger imbalances (9). In the present study, relative fascicle length was able to offset the increased risk associated with greater between-limb strength imbalances (or *vice-versa*), particularly in players with a history of HSI.

Does more regular assessment of risk factors improve our ability to predict future HSI?. The best performing model built using risk factor data assessed at multiple time points (AUC = 0.726) did not outperform the best performing model using data from a single time point (AUC = 0.681). In practical terms, the AUC of these models suggest that if we were to randomly examine a prospectively injured athlete and an uninjured athlete, the likelihood that these models would have correctly allocated the prospectively injured athlete a higher predicted injury probability (compared with the uninjured athlete) is equal to approximately 73% (multiple time point measures) and approximately 68% (single time point measures), respectively. The predictive ability of the current

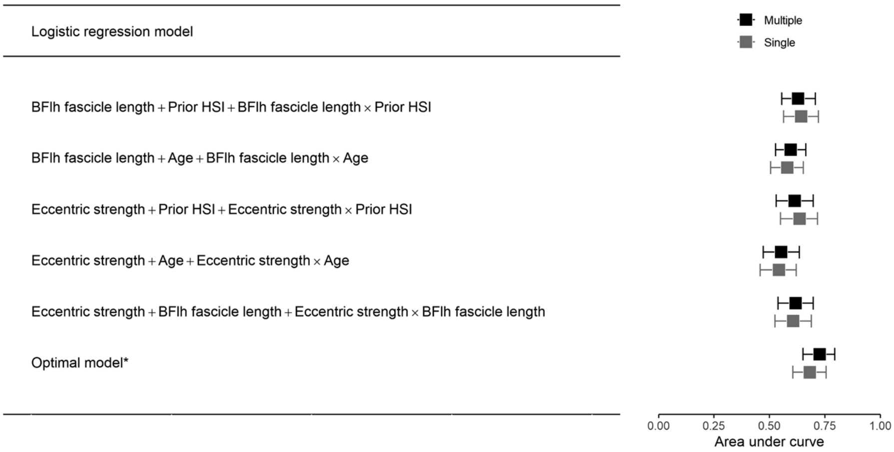


FIGURE 6—Area under the curve for the six different multivariate logistic regression models that used data collected at a single time point (*gray*; start of preseason) or multiple time points (*black*; start of preseason, end of preseason, middle of in-season) from a cohort of 455 Australian Football player seasons. *The predictor variables in the optimal model was different for the single and multiple time point models. Single time point predictor variables = prior HSI in the previous 12 months and BFlh relative fascicle length. Multiple time point predictor variables = prior HSI in the previous 12 months, BFlh relative fascicle length and eccentric knee flexor strength imbalance.

models is similar to that of previous models built using eccentric strength and fascicle length data from soccer players (AUC = 0.759) (6). Despite the current work displaying similar model performance to previous work, more regular assessment of eccentric knee flexor strength and BFlh fascicle length does not appear to offer a meaningful improvement in terms of identifying whether an athlete will suffer a prospective HSI, although the single highest AUC was derived from a model built using more regular assessments.

Limitations. Because BFlh fascicles were longer than the ultrasound field of view (14 × 4.7 mm), fascicle length was estimated using extrapolation methods (31). This approach has been validated against cadaveric data (15) and has proven highly reliable in our laboratory (intraclass correlation coefficient > 0.97), but may overestimate BFlh fascicle length when compared with extended field of view imaging (32). Not all HSI reported in this study provided details pertaining to the muscle that was injured and there was no standard classification system used (e.g., (33)). More detailed injury data may have allowed further subgroup analysis (e.g., BFlh only injuries, MRI negative and/or positive injuries). Player exposure data were not presented in the current study, which means HSI incidence was not reported relative to the amount of time spent training and competing. Accounting for player exposure to high-speed running using Global Positioning System data, may provide more insightful investigation into HSI risk. Due to data being collected across multiple teams as part of their routine practices, warm up procedures for the strength assessments were not standardized. Limiting the impact that varied warm up practices may have on the strength outcomes should be considered as part of future research.

CONCLUSIONS

We have provided novel evidence that the performance of models attempting to identify HSI risk in Australian Football players was closer to random chance than perfect prediction and was not improved by more regular assessments of HSI risk factors.

Conflicts of interest and source funding: D. A. O. is listed as a coinventor on a patent filed for a field-testing device of eccentric hamstring strength (PCT/AU2012/001041.2012) and is a minority shareholders in Vald Performance Pty Ltd, the company responsible for commercializing the device. The association between measures derived from the device and future hamstring strain injury is directly examined in this article. D. A. O. has received research funding from Vald Performance, for work unrelated to the current article. D. A. O. is also the Chair of the Vald Performance Research Committee, a role that is unpaid. D. A. O.'s brother is an employee and minor shareholder in Vald Performance. D. A. O.'s brother-in-law is an employee of Vald Performance.

M. D. W. is a member of the Vald Research Committee. M. D. W. has been provided donations of equipment, and funds for travel and subsidence by Vald Performance to conduct research unrelated to this project. M. D. W. has received payment for reports for Vald Performance unrelated to this and any research study. J. D. R. is currently an employee of Vald Performance Pty Ltd, the company responsible for commercializing the field testing device of eccentric hamstring strength used in the current study. J. D. R.'s primary contribution to this article occurred before his employment at Vald Performance. J. D. R. is also a minority shareholder in Vald Performance Pty Ltd. M. N. B. is a former employee of Vald Performance Pty Ltd, the company responsible for commercializing the field testing device of eccentric hamstring strength used in the current study. M. N. B. was not employed by Vald Performance at any stage during the conduct of this study. M. N. B. has also previously received funding from Vald Performance for research unrelated to the current article. No other authors declared any conflicts.

The results of the present study do not constitute endorsement by ACSM.

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

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