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The Relationship Between Running Load, Strength, Muscle Architecture and Hamstring Strain Injury Across Two Seasons of Elite Male Australian Football: A Prospective Cohort Study

Ray Breed[1,2,4,9*], David A. Opar[2,4], Rich D. Johnston[3,4,5], Jack T. Hickey[4,6], Morgan D. Williams[7,8], Nirav Maniar[2,4] and Ryan G. Timmins[3,4]

Abstract

Background Previous research has demonstrated a relationship between modifiable (e.g. hamstring strength, muscle fascicle length and high-speed running load), non-modifiable factors (e.g. age, previous injury) and hamstring strain injury (HSI) risk. However, these factors have mostly been assessed in isolation and no study to date has investigated the associations between running load, strength and muscle architecture with HSI risk. The study aim was to explore the interactions between modifiable HSI risk factors that are commonly assessed within elite Australian footballers.

Methods A prospective cohort study design. Eccentric knee flexor strength and biceps femoris long head (BFlh) fascicle lengths were measured in 299 unique elite-level Australian Football players (age 24 ± 4 years, height 188 ± 8 cm, and weight 87 ± 9 kg) during two pre-seasons. Data from wearable micro-sensor units (high-speed running at ≥ 24k/hr and total distance) were collected over two seasons of elite Australian Football.

Results Across 408 player-seasons there were 67 HSIs (16.4%), which took an average of 17 ± 10 days and 23 ± 12 days to return to full training and competitive matches, respectively. Univariate analysis showed that BFlh pennation angle (OR 1.6, 95% CI 1.2–2.2), fascicle length (OR 0.6, 95% CI 0.5–0.9), weekly high-speed running distance (OR 1.7, 95% CI 1.2–2.4), weekly change in total distance (OR 1.5, 95% CI 1.1–2.2) and weekly change in high-speed running distance (OR 1.6, 1.2–2.2) were significantly different between the injured and uninjured group ($P < 0.05$). Combining strength and architectural variables of BFlh pennation angle, fascicle length and peak force was able to explain 12% of variance in the risk of sustaining a HSI. The addition of running load exposure variables of weekly distance and change in weekly distance to the multivariate model increased the explained variance to 20%.

*Correspondence:
Ray Breed
r.breed@federation.edu.au; raybreed5@gmail.com

Full list of author information is available at the end of the article

Conclusion Combining measures of running load exposure with hamstring strength and architecture, increases the variance explained by multivariate models for determining HSI risk. Despite this, there was still approximately 80% of unexplained variance in sustaining a HSI in this study.

Key Points

- Running load, eccentric knee flexor strength and biceps femoris long head (BFlh) architectural variables were measured in this study, with pennation angle, fascicle length, weekly high-speed running, weekly change in total distance and weekly change in high-speed running each having a significant association with HSI risk ($P < 0.05$) in isolation.
- Multivariate modelling showed that a combination of five variables of BFlh pennation angle and fascicle length, eccentric knee flexor strength, weekly distance and weekly change in distance had the strongest association with HSI risk.
- However, these variables when combined only explained ~ 20% of the variance, leaving 80% of the difference between injured and non-injured players unexplained by the variables measured in this study.

Background

Hamstring strain injury (HSI) incidence rates remain high and have not decreased over the past 30 years within field-based team sports [1]. In the elite Australian Football League (AFL), each team reports an average of seven HSIs per season [2]. Due to this high incidence, HSIs have major financial [3] and performance implications [4] for the injured player and their team. Australian Football is a dynamic and physically demanding intermittent team sport, played across four × ~25 to 30-minute quarters, with an average of ~ 13 km of total distance covered by a player, including high-speed running efforts, sprinting, accelerating and decelerating [5, 6]. Most HSIs in the AFL occur during these high-intensity running-related movements [2, 7]. Contributing factors could include the hamstrings being subjected to high levels of force and strain, particularly during the late swing phase of running [8, 9], or "poor" running mechanics with pelvic instability or increased hip flexion [10, 11].

Greater weekly high-speed running distances (≥ 24 km/h) have been shown to relate to HSI when 4 weeks preceding each injury was standardised to the players' 2 year session average [7]. Similarly, Ruddy et al. [12] found that HSI risk was higher in the week following greater high-speed running distances at >24 km/h. However, both these studies were within single teams with relatively small sample sizes. Conversely, there are conflicting findings within similar team sports (e.g. rugby, soccer), potentially due to differing speed threshold and player load definitions, regarding whether higher or lower running loads and/or load variability in total distance or high-speed running (e.g. week to week) contribute to an increased risk of sustaining a HSI [13–15].

Running load in team sports is widely measured using Global Navigation Satellite Systems (GNSS) to quantify physical or exertional output, with the aim of improving player performance and reducing injury risk [16]. There is no consensus definition of player load, with several variables relating to speed and distance commonly monitored in field-based team sports [17]. In men's soccer, the most frequently used threshold to measure high-speed running is >19.8 km/h [18], whereas studies in the AFL range more broadly from >14.4 km/h [19], >19.8 km/h [20] and >24 km/h [7]. The amount of tissue strain and muscle forces on the hamstrings increase exponentially as running speed increases towards maximal effort sprinting [21, 22], and therefore differences in speed threshold definitions could contribute to the disparity in findings within the running load and injury research. Exposure to high-speed running and sprinting appears to influence increases in biceps femoris long head (BFlh) fascicle length [23] and eccentric strength [24], which may translate to a potential preventive effect on HSIs [25]. However, it is unclear what influence changes in running loads, including high-speed running and sprinting, might have upon prospective HSI risk [26, 27].

Running load including total distance and high-speed running [7, 28], eccentric knee flexor strength [29–31], between limb strength imbalance [32, 33], and BFlh fascicle length [34, 35], are all modifiable risk factors that have been associated with HSI. Most risk factor studies have investigated the univariate association between one of these factors and the occurrence of HSI in isolation, without exploring the interactions of these risk factors [30]. In addition, non-modifiable factors, such as older age and prior injury, have demonstrated an increased risk of HSI in Australian Football and other intermittent team sports [30, 36–38]. Previous research suggests that there may be an interaction or mediating effect between age, prior hamstring injury and modifiable risk factors such as hamstring strength [29] and BFlh fascicle length [34], which could influence the risk of sustaining a HSI [39]. Training programs including eccentric hamstring exercises have been associated with HSI reduction [40, 41], although the underlying mechanism for these programs' effectiveness is unclear [10, 42]. It is also unknown if there are potential relationships between multiple risk factors – for example, if greater strength or architecture could reduce the negative effect of large changes in running load or high-speed running. Consequently, research exploring the interaction of risk factors could be important [30].

Therefore, the aims of this study were to: (a) investigate univariate associations between previously recognised HSI risk factors and prospective rates of HSI in elite-level Australian Football, then (b) explore multivariate associations between these factors and HSI risk.

Methods

Study Design and Participants

This prospective cohort study was conducted with participants who were professional male Australian Football players, participating in the elite-level AFL competition. Teams competing within the AFL were invited to participate, with four teams participating during 2017/18 and a further two teams (six in total) during the 2018/19 AFL seasons. Data were collected from the pre-season of November 2017 to the end of the competitive season in August 2019. We recognise that there is limited research in elite women's team sport, however, the AFLW (women's top competition) started in 2017 as a semi-professional (part time) competition of just eight teams with no data available from clubs. Ethics approval was granted by the university Human Research Ethics Committee (No: 2017–208 H). Each included player provided informed written consent to participate in the study prior to each pre-season testing. Players were excluded from the season if they were unable to fully complete the initial strength and architecture testing. Part of this data has been published in other studies [33, 43] addressing different research questions to the current study.

Testing Procedures

Club medical staff (i.e., medical doctor or physiotherapist) completed a standardised form for every player before each season, that included descriptive details (e.g., age, height and weight) and retrospective information pertaining to relevant injury history (e.g., previous HSI, history of anterior cruciate ligament injury). Players then underwent testing of their eccentric knee flexor strength and BFlh architecture within the first six weeks of each pre-season. The GNSS data collected from training sessions and matches from pre-season and in-season was used for analysis. Any HSI occurrences within this timeframe were included in the study (a total of 35 weeks per season) (Supplementary Information Fig. 1). A HSI was defined as posterior thigh pain that resulted in the termination of exercise and then confirmed by a physical examination of the injury by the team doctor/physiotherapist. When an injury was confirmed, a standardised injury report form was completed by the club medical staff for the player who incurred a HSI.

Eccentric Knee Flexor Strength

Eccentric knee flexor strength was assessed during the Nordic Hamstring Exercise (NHE) and measured on an instrumented device (NordBord, VALD Performance, Queensland, Australia) [33]. The NHE conducted using the NordBord has previously shown high to moderate test-retest reliability [44] and high test-retest reliability and good validity [45]. Sport science staff of each team performed their own testing, following both verbal and written protocols provided by the research team. Staff and participants were all familiar with the NHE and performed it regularly as part of their training and monitoring. After a self-selected warm-up, participants were instructed to have their arms crossed over the chest, keep a neutral position of the trunk and hips, then gradually lean forward whilst resisting the movement and pulling up maximally against the ankle hooks of the testing device. Players performed up to three maximal effort repetitions, depending on the practices used by each team. Absolute peak force (N) was measured for each leg to calculate bilateral eccentric knee flexor strength (average of both legs) and between-leg imbalance as a percentage.

Architecture of Biceps Femoris long Head

Fascicle length, pennation angle and muscle thickness of the BFlh were measured using the same method of previously reported studies [46–48]. Participants at each club were assessed by the same experienced researcher (RT) with previous high intra-class reliability [49] whilst lying prone on a massage plinth with the knee joint fully extended. Architectural variables were calculated by using 2-dimensional ultrasound images (12 MHz frequency, 8 cm depth, 14 × 47 mm field of view; GE Healthcare Vivid-I, Wauwatosa, USA) taken along the longitudinal axis of the BFlh muscle belly using the half-way point between the knee joint fold and the ischial tuberosity for both legs. Images were analysed offline (MicroDicom, V.0.7.8, Bulgaria) with all measurements performed by the same assessor (RT). Fascicle length was defined as the length of a clearly identified fascicle between aponeuroses. As the entire fascicle was not visible, total length was estimated using a validated Eq. (50): $FL = \sin(AA + 90^0) \times MT/\sin(180^0 - (AA + 180^0 - PA))$, where FL is the fascicle length, AA the aponeurosis angle, MT the muscle thickness, and PA the pennation angle. Muscle thickness was calculated by the distance between the superficial and intermediate aponeurosis of the BFlh, and pennation angle measured using the angle between the intermediate aponeurosis and the fascicle of interest (Fig. 1).

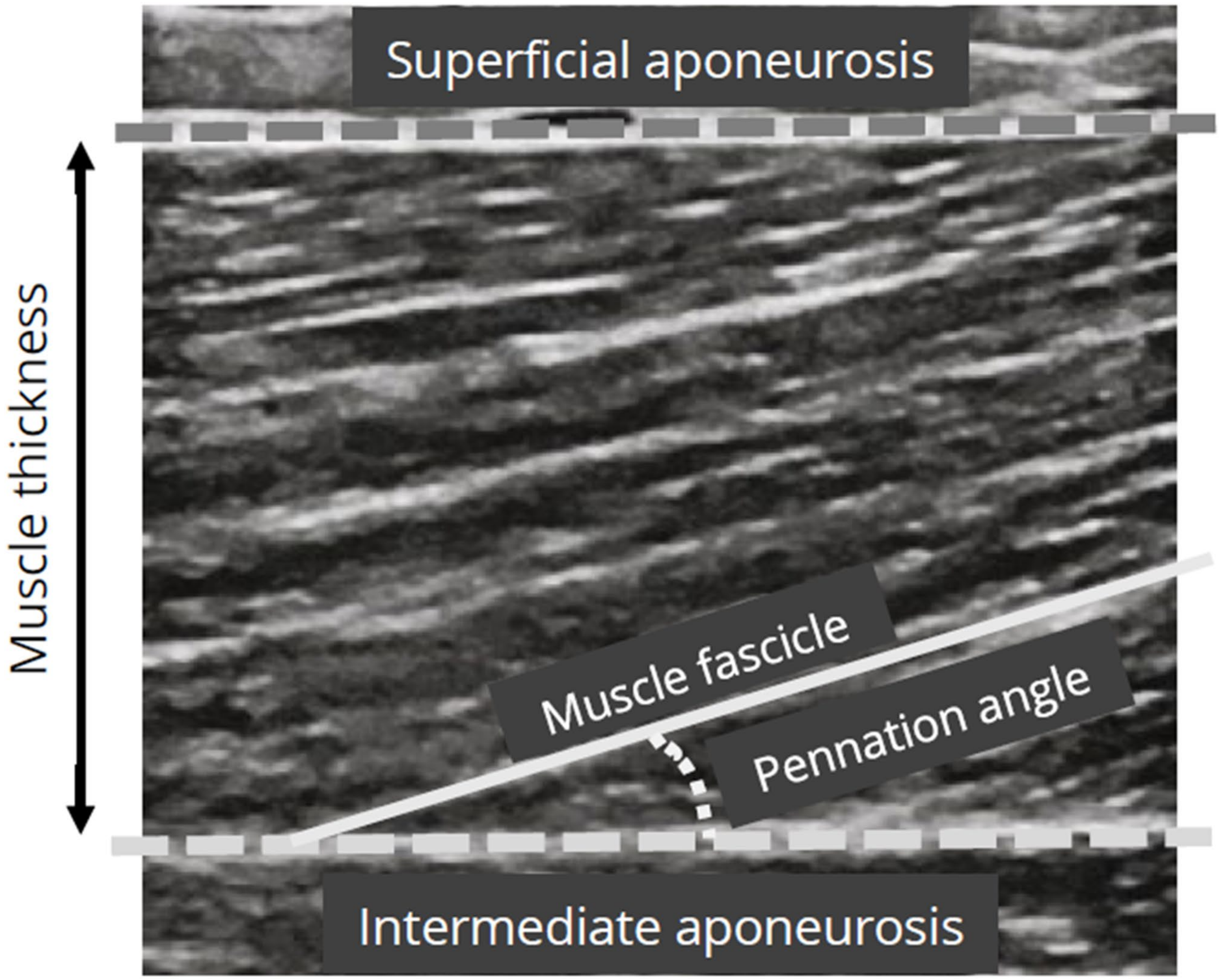

Fig. 1 Biceps femoris long head two-dimensional ultrasound image and architectural measurements taken along the longitudinal axis of the posterior thigh. The muscle thickness is calculated as the distance between the superficial and intermediate aponeuroses. The angle between the muscle fascicle and intermediate aponeurosis is the pennation angle. Estimate of fascicle length is calculated using muscle thickness and pennation angle using trigonometry

Running Load

To measure running load exposures, each club collected GNSS data for every training session and match then recorded as weekly totals across the two seasons using 10-Hz Optimeye S5 microtechnology units (Catapult Sports, Victoria, Australia). These devices have been shown to offer acceptable validity, intra- and inter-unit reliability for GNSS-derived metrics [50]. Prior to each training session or match, the units were fitted into a specially designed pocket in the clothing worn, which was positioned between the participant's scapulae. Each player was allocated the same GNSS unit for every session. GNSS-derived measures included weekly total distance (m) and weekly total high-speed running, which was defined as the distance (m) covered ≥ 24 km/h [7]. To capture variability in running load exposure, the average absolute change in total distance and high-speed running distance was calculated for each player by using the distance of the current week, less the distance covered in the previous week (expressed as an absolute value), then averaged over all weeks prior to the injury. For the non-injured player seasons, all recorded weeks until the end of the season were included.

Reporting of Hamstring Strain Injuries

Following the diagnosis of a HSI, the medical staff completed a standardised injury report form that included details such as the date of the injury, leg injured (left or right), muscle injured, mechanism causing injury, and the number of days to return to full training and return to play. An injury occurring for the first time in a season was recorded as an index injury. There were no recurrent injuries (defined as another HSI of the same leg in the same season) in this study. However, if a player sustained a HSI in each season, data collection stopped after the first HSI, then resumed in the second season with a 'prior HSI' being recorded as a variable.

Data Analysis

Data were analysed in the R Studio environment (version 2022.02.1, Posit, Boston, MA, USA) using the R statistical computing language (*Innocent and Trusting*, R Foundation for Statistical Computing, Vienna, Austria). As variables were on different scales, they were mean centred whereby the mean was equal to zero and the standard deviation equal to one. Firstly, the influence of each variable on HSI risk was assessed using generalised linear mixed models with a binomial distribution for the outcome variable (HSI Y/N) using the *glmer* function from the *lmerTest* package. Second, multivariate generalised linear mixed models were built for [1] hamstring strength and architecture [2], running load, and [3] a combined hamstring strength/architecture and running load model. The variables included in each model were first informed by the univariate analysis and previous research [29, 34, 51]. The fit of each of the 3 models was assessed using the Akaike Information Criterion (AIC), a significant reduction in AIC using the *anova* function indicated an improved model fit. A marginal R^2 was used to determine how much variance was explained by each model using the *r.squaredGLMM* function. The association of each variable on HSI risk was estimated using odds ratios (OR's) and 95% confidence intervals extracted by taking the exponent of the model estimates.

Results

Participants and Injury Descriptives

There were 299 players included in this study with a mean age of 24 ± 4 years, height 188 ± 8 cm, and weight of 87 ± 9 kg. Of these players, 190 were involved in both seasons and 109 included in one of the seasons. Across the 408 player-seasons, 67 HSIs were sustained (16.4%), while 341 player-seasons did not result in any HSIs (83.6%). Figure 2 displays the weekly distribution of HSIs across both AFL seasons combined. Thirty-eight (11%) of non-injured player-seasons had recorded a previous

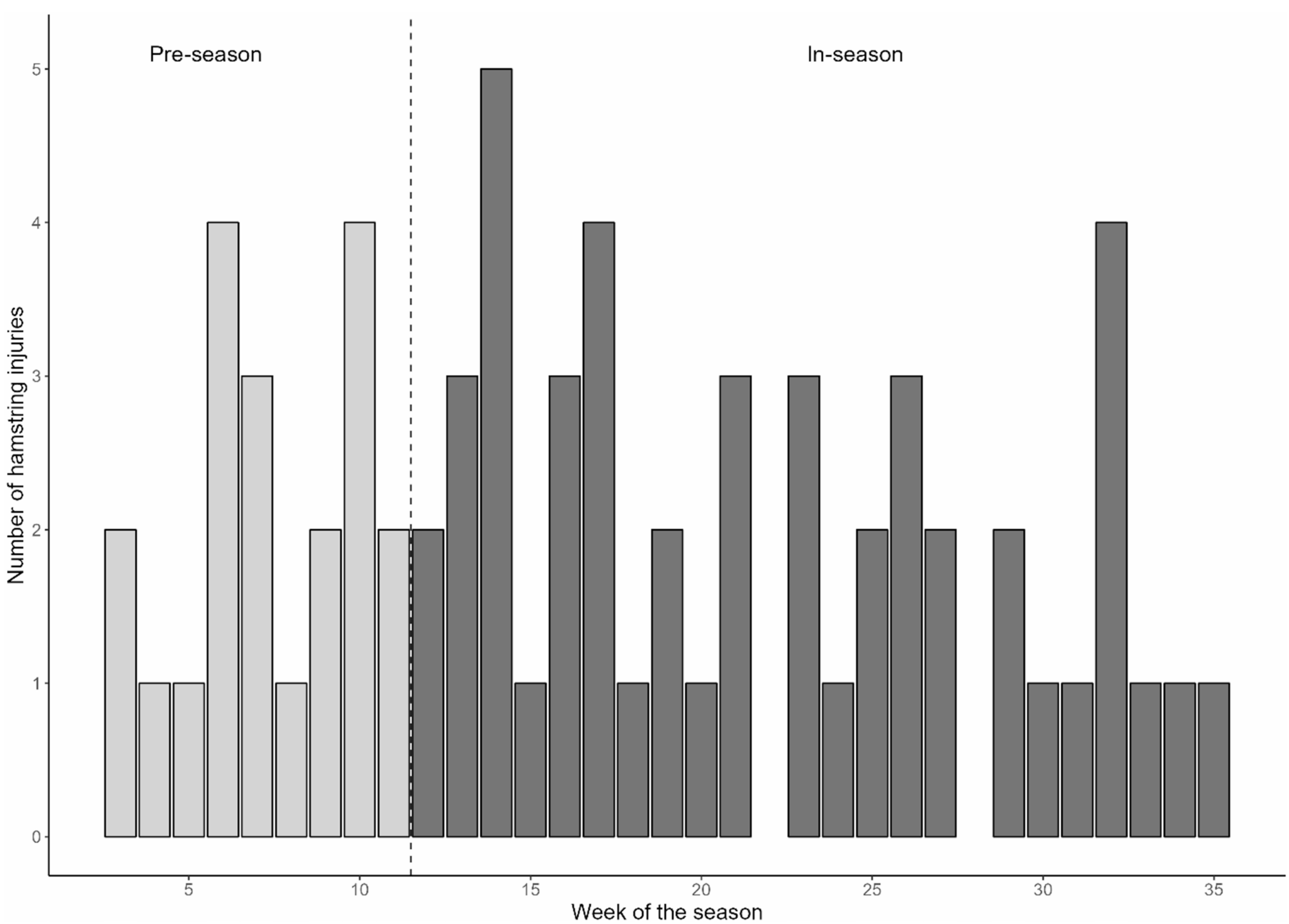

Fig. 2 Weekly distribution of hamstring strain injuries across two Australian Football League (AFL) seasons, with season 1 and season 2 injuries combined. Week 1 represents the first week of data used for this study during the pre-season training period. Pre-season data was collected for 11 weeks then an in-season that consisted of weekly competitive matches and training for a further 24 weeks (total of 35 weeks of data collected for each season)

Table 1 Univariate descriptives and statistical analyses of non-modifiable and modifiable variables

Variable	Non-injured (*n* = 341) Mean ± SD	Injured (*n* = 67) Mean ± SD	Odds ratio (95% CI)	Z statistic	*P* value	R^2
Age (years)	23.6 ± 3.8	24.0 ± 4.0	1.3 (0.6 to 3.0)	0.585	0.558	0
Height (cm)	188.2 ± 7.7	187.5 ± 7.1	0.9 (0.7 to 1.3)	-0.468	0.640	0.001
Body weight (kg)	86.5 ± 8.9	86.6 ± 8.6	1.5 (0.6 to 3.4)	0.919	0.358	0.001
Muscle thickness (cm)	2.6 ± 0.3	2.7 ± 0.2	0.9 (0.4 to 2.1)	-0.254	0.799	0
BFlh pennation angle (deg)	15.5 ± 1.3	16.0 ± 1.1	1.6 (1.2 to 2.2)	2.881	*0.004**	0.047
BFlh fascicle length (cm)	10.3 ± 0.6	10.0 ± 0.7	0.6 (0.5 to 0.9)	-2.548	*0.011**	0.038
Peak force (N)	444.9 ± 66.3	429.7 ± 72.1	0.6 (0.2 to 1.6)	-1.014	0.310	0.001
Peak force asymmetry (%)	10.8 ± 11.0	9.2 ± 7.0	1.2 (0.5 to 2.4)	0.364	0.716	0
Weekly distance (m)	16,810 ± 7701	19,517 ± 6343	2.2 (0.8 to 5.7)	1.593	0.111	0.004
Weekly HSR (m)	294.3 ± 175.7	379.8 ± 170.1	1.7 (1.2 to 2.4)	2.784	*0.005**	0.052
Weekly change in distance (m)	5635 ± 2582	6702 ± 2636	1.5 (1.1 to 2.2)	2.317	*0.021**	0.032
Weekly change in HSR (m)	148.4 ± 84.9	192.7 ± 99.1	1.6 (1.2 to 2.2)	2.957	*0.003**	0.050

HSR high-speed running, *SD* standard deviation

*Significant difference ($P < 0.05$) between non-injured and injured group

Table 2 Comparison of three multivariate regression models

Model	Variable	Odds ratio (95% CI)	Z statistic	*P* value	R^2
Strength & Architecture	BFlh pennation angle (deg)	1.7 (1.2–2.5)	2.942	*0.003**	0.119
	BFlh fascicle length (cm)	0.7 (0.5–0.9)	-2.392	*0.017**	
	Peak force (N)	0.8 (0.5–1.1)	-1.674	0.094	
Running load	Weekly distance (m)	2.4 (0.6–10.5)	1.182	0.237	0.009
	Change in weekly distance (m)	2.7 (0.9–8.2)	1.794	0.073	
Combined	BFlh pennation angle (deg)	1.8 (1.2–2.6)	2.880	*0.004**	0.195
	BFlh fascicle length (cm)	0.7 (0.5–0.9)	-2.445	*0.014**	
	Peak force (N)	0.6 (0.4–0.9)	-2.246	*0.025**	
	Weekly distance (m)	1.4 (0.9–2.2)	1.603	0.109	
	Change in weekly distance (m)	1.6 (1.1–2.3)	2.377	*0.017**	

HSR high-speed running

*Significant difference ($P < 0.05$) between non-injured and injured groups

HSI (within the past 12-months) compared to 19 (28%) of injured player-seasons. Twenty-two (6%) of the non-injured player-seasons had sustained a prior ACL injury (during any time of their playing career) compared to four (6%) injured player-seasons. Following a HSI it took on average 16.6 ± 9.8 days and 22.7 ± 12.2 days to return to full training and match play, respectively.

Univariate Analysis

Statistically significant differences ($P < 0.05$) were found between the injured ($n = 67$) and non-injured ($n = 341$) player seasons whereby BFlh pennation angle was greater, BFlh fascicle length was shorter, weekly HSR was greater, weekly change in distance was greater and weekly change in HSR was greater in the players who sustained HSIs (Table 1). Non-modifiable variables of age, height, weight and prior ACL injury were not statistically different between groups ($P > 0.05$), whereas previous HSI was (Z statistic = 3.580, $P = 0.000$, $R^2 = 0.046$).

Multivariate Analysis

The results from three multivariate models are shown in Table 2: (a) hamstring strength and architecture, (b) running load, and (c) combined hamstring and running load model. The running load model and the strength and architecture model explained 1% and 11.9%, respectively, of the variance of sustaining a prospective HSI. However, the combined hamstring and running load model produced the best-fit with 19.5% of the variance explained. Within the combined running load and hamstring model, a higher pennation angle, shorter fascicle length, lower peak force and greater change in weekly distance all significantly increased the odds of a HSI ($P < 0.05$). This combined model offered a significantly better fit than the hamstring strength and architecture model ($P = 0.002$). The distribution of each player season in relation to weekly change in total running distance, peak eccentric knee flexor strength and BFlh fascicle length between injured and non-injured player seasons ($P > 0.05$) is represented in Fig. 3.

Discussion

To our knowledge, this is the first study to assess a combination of modifiable HSI risk factors (eccentric knee flexor strength and muscle architecture) with GNSS running load metrics and their associations with prospective HSI. Of all the multivariate models, the best performing analyses included a combination of five variables: BFlh pennation angle and fascicle length, eccentric knee flexor

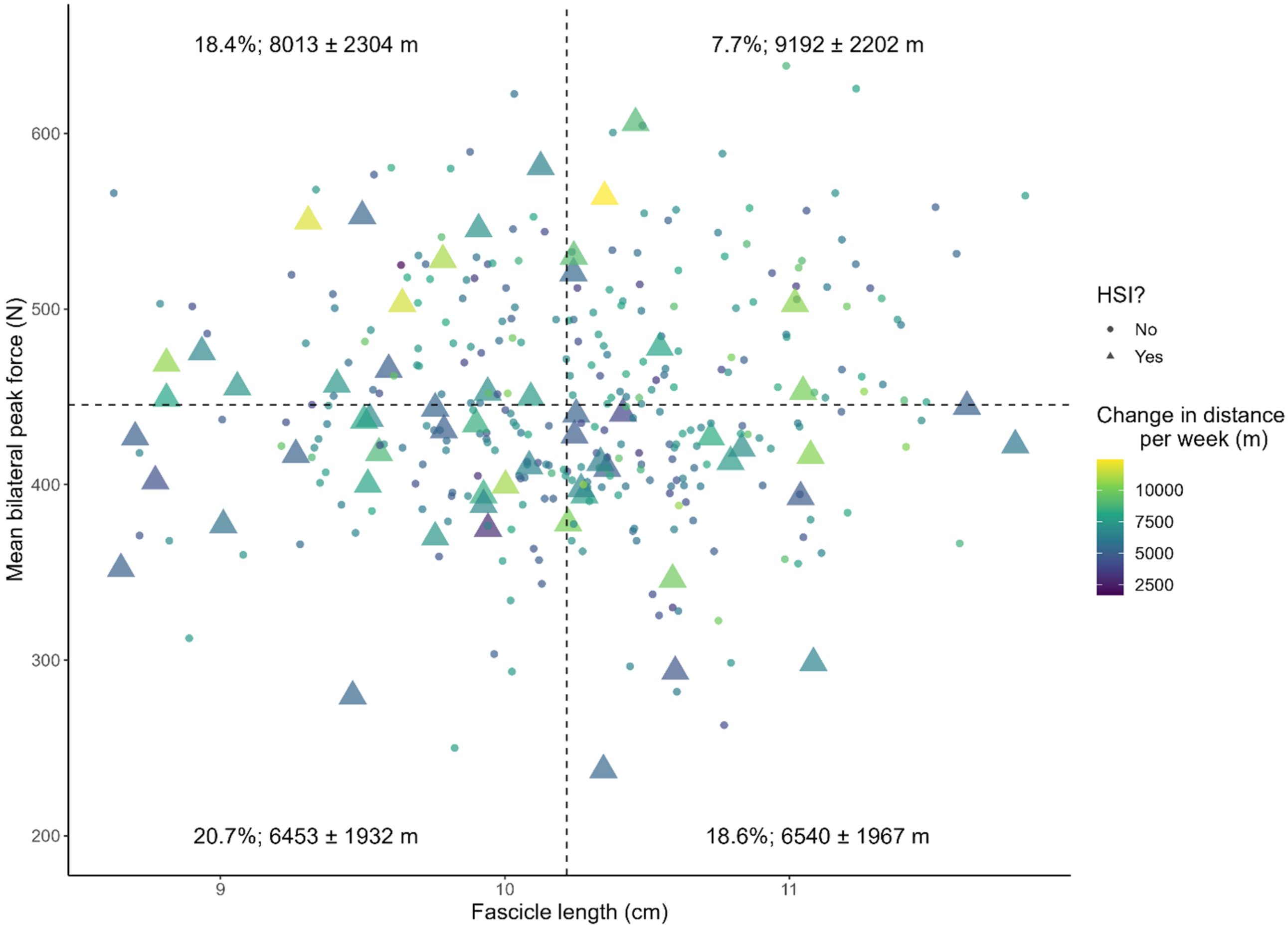

Fig. 3 Relationship between weekly change in distance, eccentric knee flexor strength and biceps femoris long head (BFlh) fascicle length with injured and non-injured player-seasons. Each quadrant represents the fascicle length and hamstring strength for each player season, with the intersection being the median of the two variables: top left = short and strong, bottom left = short and weak, top right = long and strong, bottom right = long and weak. The percentage of injury to non-injury player seasons, along with the mean and SD of the weekly change in distance, is shown in each quadrant. Large triangles represent player season injuries and small circles are player season non-injuries. Lighter shades of colour represent higher changes in weekly distance, and darker shades represent lower changes in weekly distance

strength, weekly total distance and change in weekly total distance. In isolation, there was limited value in using running load metrics to identify athletes at risk of prospective HSI, with a running load multivariate model only explaining 1% of the variance in the data. But, when running load data were combined with BFlh architecture and eccentric knee flexor strength, there was a significant positive additive effect to explain the variance associated with HSI. It is therefore feasible that muscle architecture and greater strength could help to protect against the negative impact of increased weekly distance and large changes in weekly distance on HSI risk (see Fig. 3).

Within six teams across two seasons, 67 HSIs from 408 player-seasons were recorded, making this the largest prospective HSI investigation in elite male Australian footballers utilising variables across strength, architecture and running load measures. In this study, a combined model was able to explain up to 20% of the variance associated with HSI. Although these factors are related to sustaining a HSI, there are many other variables not accounted for in this model, such as running mechanics, strength and architecture of other muscles, and that player risk factors could be dynamic and change across various time points [43]. Therefore, training design should be carefully planned and GNSS data explored across narrower windows (i.e., 2- or 3-day totals). Based on our findings, practitioners should appropriately plan and periodise player running loads to avoid large changes in distance and aim to further develop hamstring strength and increase fascicle length, ideally prior to the start of each pre-season to allow a greater chance of full training completion that focusses mostly on technical and tactical skill development.

Univariate Analyses of Hamstring Strain Injury Modifiable Risk Factors

For muscle architectural measures, greater BFlh pennation angles and shorter fascicle lengths were significantly associated with an increased risk of HSI. Eccentric knee flexor weakness combined with short fascicles have been previously shown to increase injury risk in soccer players [34]. However, neither eccentric knee flexor strength (peak force) or bilateral asymmetry were associated with HSI risk in this study when assessed in isolation, contrasting some previous findings within field-based team sports [29, 31, 32]. Opar et al. [29] measured hamstring strength during the pre-season in elite Australian footballers with the injured group (N = 27) and uninjured group averaging 246 N and 301 N, respectively. However, compared to our similar, larger cohort 5 and 6 years' later, hamstring strength of the injured and uninjured groups were approximately 43% (430 N) and 32% (445 N) higher, respectively, reflecting a greater emphasis on eccentric hamstring strengthening more recently within AFL clubs [52]. Such an increase in strength could contribute to the differences in our findings, potentially by reducing the risk of sustaining HSIs through an increased resistance to the high forces experienced when sprinting and high-speed running.

It is of great interest in high-performance sport to monitor player training and match loads, both in the long (chronic) and short (acute) term, to help inform players and staff in the delicate balance of maximising performance and minimising injury risk [26]. In our study, at the univariate level, players with higher average high-speed running distance, greater weekly changes in high-speed running distance and greater weekly changes in total distance were associated with HSI (P < 0.05). Although weekly total distance had the highest odds ratio of all univariate factors (OR = 2.2, 95% CI 0.8–5.7) with ~ 14% higher average weekly distance for injured players, large variations between players limited its univariate association with injury. Some prior research in other sports have shown that higher chronic running loads could have a protective effect [15, 28], but similar to our findings, a greater variability or large 'spikes' in weekly running distance can increase the risk of injury [15, 53].

However, without an accepted and validated method of calculating running load or changes in running load, it limits comparison between studies, with conflicting findings in the research relating to high-speed running load or total distance [26] – in particular whether low loads or high loads are related to HSI. We found that no single running load variable could explain more than 5% of the variance of sustaining an injury on its own. Training load could be important, but considering it as a factor in isolation as a management tool for practitioners has limited ability to predict an injury [54]. Our research then aimed to explore if adding hamstring strength and/or muscle architectural variables to running load measures could strengthen the association with future injury.

Multivariate Analyses of Risk Factors and their Association with HSI

A combined model that included five variables: BFlh pennation angle, BFlh fascicle length, eccentric knee flexor strength, weekly total distance and the change in weekly total distance, performed the best in determining the risk of a future HSI. However, only 20% of the variance explaining the risk of HSI could be accounted for using this model. The inclusion of non-modifiable factors as co-variates, such as age, previous HSI or ACL injury, did not improve the predictive capacity of any multivariate model. However, other research has regularly found significant univariate relationships between older age, previous HSI, ACL injury or calf strain injury, with the risk of sustaining an index HSI or subsequent HSI [1, 30].

Previous research has focussed on investigating the independent relationships between risk factors and HSI risk, without exploring the potential interactions between these variables [30]. Although several modifiable variables were significantly related to HSI risk in our study, no one variable accounted for more than 5% of the variability, perhaps demonstrating the limited value of including running load data, strength or muscle architecture alone to predict HSI risk. It is generally accepted that high-speed running and sprinting, eccentric knee flexor strength and BFlh fascicle length might all have independent associations with HSIs, but their interactions and subsequent combined effect on HSI risk has not been previously researched. Our findings help to demonstrate the multifactorial nature and complexities of determining the future risk of a HSI, which could be variable between individuals, with unique combinations and associations of risk factors. In addition, risk factors could be dynamic in that they could change throughout the course of a season and at different time points of measurement [43]. However, Opar et al. [33] showed that using more regular strength and architectural testing did not improve the predictive capacity of sustaining a HSI. Whilst testing for risk factors more regularly could be potentially useful, in the context of professional sport it is not always practical to test multiple times within a season to risk further contributing to injury with short turnaround times and recovery between matches.

When running load data was combined with other factors in a multivariate model, there was a positive or additive effect of up to 20% explained variance. Players with greater strength and muscle architectural factors at baseline measured during pre-season, could help to reduce the impact of increased running distance and larger changes in weekly running distance on HSI risk (Fig.

3). Whilst we examined the association between common risk factors and HSI, the large unexplained variance would suggest that we are unlikely to be able to predict future HSIs, even with the best performing multivariate model [55]. Potential risk factors not measured in our study that could partially contribute further to the unexplained variance and differences between individual players, could be the specific anatomy of the muscle-tendon unit [56, 57], muscle activation patterns during higher-speed running [58, 59], horizontal force production [60], hip extension strength and gluteal muscle activity [61, 62] and sprinting mechanics [10], among others. Whilst it would be extremely challenging to measure every possible risk factor in each athlete, an understanding of the many risk factors and their potential associations with injury can assist practitioners in better monitoring and managing injury risk in players.

Screening for hamstring risk factors, such as strength, architecture and running load, appear to be limited in predicting future HSIs. However, our study also highlighted risk factors that had statistically significant associations with HSI, indicating that screening for risk factors might still be of value in elite sport. By highlighting potential variables that might be associated with an increased risk of a HSI, practitioners can then address risk factors through a targeted intervention in an attempt to improve HSI prevention.

Limitations

We acknowledge this study has several limitations. As participants were elite males, the findings cannot be generalised to elite female footballers. Eccentric knee flexor strength and architectural measures were taken only once during the pre-season, therefore not reflecting any potential changes that could occur throughout the season. Whilst more research needs to be done in this area, Opar et al. [33] showed that more regular testing did not improve the predictive value of the tests. When measuring BFlh fascicle length, they were longer than the ultrasound field of view (14 × 47 mm), so the length was estimated using extrapolation methods [49]. Although this approach may overestimate BFlh, it has excellent reliability (ICC >0.97), has been validated against cadaveric data [63] and established as a modifiable HSI risk factor using this method. Each club provided players' GNSS data as a weekly total, rather than daily measures. Therefore, day-to-day variability or load 'spikes' within a calendar week could not be reported. Although each team used the same GNSS model and software, there might have been small variations in protocols and data inclusion/exclusion criteria, potentially leading to inter-club variations. High-speed running was defined as ≥ 24 km/h, so exposure to very high speeds/sprinting or other movements (e.g. accelerations, directional changes) were not separately accounted for, which might have different mechanisms that might either protect or promote injury. Whilst using set absolute speed thresholds for all players is common practice in the research [5, 6], it does not address individual physiological variations, such as top speed and maximal aerobic speed, and therefore might not be reflective of a player's actual physical exertion.

Conclusions

This study demonstrates that measuring eccentric knee flexor strength, BFlh architectural or running load metrics on their own provides limited predictive capacity to identify male athletes at risk of future HSI. However, combining a measure of running load exposure (i.e. total weekly distance), along with hamstring strength and architecture, increases the variance explained by the models aimed at identifying HSI risk. Despite this, there was still approximately 80% of unexplained variance in sustaining a HSI in this study. This demonstrates the potential individual player differences and multi-factorial nature of HSIs, suggesting that there is no "one-size fits all" model for all players. It is likely that a combination of various risk factors might be unique to each player, and therefore player screening of multiple risk factors might assist in reducing the incidence of injury and consequently, improve team performance.

Practical Applications

Our findings suggest that a combination of risk factors increase HSI risk and therefore screening each player for multiple risk factors could be beneficial, as part of injury prevention practices. Whilst the mechanism behind various running load measures increasing HSI risk is unknown, our results support the importance of load monitoring to identify high chronic running distances, high-speed running loads or high variability in running loads. The risk of these load measures on HSI are exacerbated when players have lower levels of pre-season strength and muscle architecture, therefore careful training design and planning should be considered for each player to address weaknesses of these modifiable risk factors.

Abbreviations

HSI	Hamstring strain injury
BFlh	Biceps femoris long head
AFL	Australian Football League
GNSS	Global navigation satellite system
NHE	Nordic hamstring exercise

Supplementary Information

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Supplementary Material 1.

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Author Contributions
RT, DO, JH, NM and MW conceived and designed the study. RT, JH, DO and NM conducted the performance testing and collated the running load data. RT conducted the ultrasound architectural measurements. RJ, MW and RB performed all data and statistical analysis. RB, RJ and RT wrote the manuscript. All authors read, edited and approved the final submitted version of this manuscript.

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Data Availability
The datasets generated during and/or analyzed during the current study are not publicly available due to no specific ethics approval to provide the club data.

Declarations

Ethics Approval and Consent to Participate
This study was approved by the Australian Catholic University Research Ethics Committee (No: 2017–208 H). The study was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments. Each player provided written informed consent prior to participation in this study.

Consent for Publication
Not applicable.

Competing Interests
Ray Breed, Rich Johnston, Jack Hickey, Nirav Maniar and Ryan Timmins declare that they have no conflicts of interest. Prof David Opar is listed as a co-inventor on a patent (PCT/AU2012/001041.2012), filed by the Queensland University of Technology (QUT), for a field-testing device of eccentric hamstring strength, which is now known commercially as the NordBord. Prof Opar has received revenue distributions from QUT based on revenue that QUT has generated through the commercialisation of his intellectual property. Prof Opar is a minority shareholder in Vald Performance Pty Ltd, the company responsible for commercialization of the NordBord, which is investigated as part of the current study. Prof Opar has received research funding from Vald Performance, for work unrelated to the current manuscript. Prof Opar was previously the Chair of the Vald Performance Research Committee, a role that was unpaid. Prof Opar has family members who are minor shareholders and/or employees of Vald Performance. Prof Opar was partly responsible for the design of the current study as well as reviewing drafts of the manuscript. A/Prof Morgan Williams, is employed by VALD Performance Pty Ltd.

Author details
[1]Institute of Education, Arts and Community, Federation University, Berwick, VIC, Australia
[2]School of Behavioural and Health Sciences, Australian Catholic University, Melbourne, VIC, Australia
[3]School of Behavioural and Health Sciences, Australian Catholic University, Brisbane, QLD, Australia
[4]Sports Performance, Recovery, Injury and New Technologies (SPRINT) Research Centre, Australian Catholic University, Melbourne, Australia
[5]Carnegie Applied Rugby Research Centre (CARR), Carnegie School of Sport, Leeds Beckett University, Leeds, UK
[6]Department of Sport Science and Nutrition, Maynooth University, County Kildare, Ireland
[7]School of Health Sciences and Social Work, Griffith University, Gold Coast, Australia
[8]VALD Performance, Brisbane, Australia
[9]Department of Health and Biostatistics, Swinburne University of Technology, Melbourne, VIC, Australia

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