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Eccentric Hamstring Strength Monitoring to Predict Injury Risk in Men's Non-League Professional Football: An Exploratory Cox Regression Study

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Abstract

Hamstring-strain injuries (HSIs) are the most prevalent time-loss injuries in professional football. While player monitoring of muscular strength is ubiquitous in professional football, the utility of in-season testing for predicting HSI in non-league football (NLF) settings is unclear. This study aimed to investigate if short-term, in-season changes in eccentric hamstring strength are associated with HSI risk and compare the predictive performance to a baseline model. This was a single-season prospective cohort study (36 weeks) in 20 male professional NLF players (nine HSI events). Eccentric hamstring strength was measured twice weekly during Nordic hamstring exercise (NHE) using a NordBord device. Cox proportional hazard models (Andersen–Gill) evaluated the association of HSI with bilateral peak force and inter-limb asymmetry as time-varying and baseline predictors. Nine HSIs occurred (29% of all time-loss injuries; n = 31). The predictive analysis revealed that the baseline model with hazard ratio (HR) of 0.20 (95% CI: 0.09–0.46; C-index = 0.824) outperformed the time-varying model (HR 0.29; 95% CI: 0.15–0.56; C-index = 0.776), with higher bilateral peak force protective across both models. Conversely, inter-limb asymmetry showed no association with HSI risk (HR 1.10; 95% CI: 0.95–1.27; C-index = 0.527). A key related finding was that while single test inter-limb asymmetry measurements were unreliable, stability across the season was good (ICC(1,k) = 0.895). In this cohort, a greater bilateral peak force was protective against HSI, with baseline testing more effective than twice-weekly in-season testing. Inter-limb asymmetry did not predict HSI, and the utility of its isolated use remains unclear despite the stability of players' season-long profiles. These exploratory findings require confirmation in larger cohorts.

Keywords: soccer; muscle strength; survival analysis; risk factors; Nordic hamstring exercise

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1. Introduction

Physical workloads in men's professional football have increased over the last decade [1] with a concomitant rise in hamstring strain injury (HSI) rates [2,3]. The impact of HSIs is substantial, affecting player availability and career longevity, while imposing performance costs on clubs [4,5]. Despite their prevalence, the aetiology of HSIs is complex,

with intrinsic (e.g., age and injury history) and extrinsic (e.g., fatigue) risk factors contributing to injury occurrence [6]. Consequently, eccentric hamstring strength, quantified via tests such as the Nordic hamstring exercise (NHE) using a NordBord, is a common screening metric for HSI risk [7]. However, its predictive value for HSIs is debated [8].

Sprinting, specifically the late swing phase, imposes high eccentric demands upon the hamstrings in a lengthened position [9,10], with the biceps femoris lengthened undertension by approximately 12% compared to an upright posture [11]. Football match-play also induces high levels of neuromuscular fatigue, which transiently reduces hamstring eccentric strength [12] and knee and pelvis control [10]. For example, NHE testing demonstrated significantly lower eccentric force values for 48 h following a competitive football match compared to 24 h pre-match [13]. Similarly, isokinetic testing of the hamstrings was impaired from baseline until 48 h post-match [14], while isometric maximal force may be reduced for 72 h [15]. Collectively, these impairments in hamstring function may increase HSI risk in the days after prior football exposure, which infrequent NHE testing may not capture.

Identifying at-risk players remains challenging as screening tests often fail to capture the dynamic nature of injury [10,16,17], as exemplified by the inconsistent findings of NHE thresholds [8]. Furthermore, pre-season testing of eccentric hamstring strength is not predictive of future HSI [18]. A systematic review also concluded that periodic pre- and mid-season testing were not predictive of future HSI [18,19]. Monitoring in-season eccentric strength with higher temporal resolution may therefore detect short-term decrements that signal windows of elevated HSI risk. To capture this, a time-to-event analysis with time-varying covariates dynamically updates risk as strength fluctuates throughout a season and provides a temporally accurate assessment of injury risk.

Inter-limb strength asymmetry is the relative difference in strength between the left and right limbs [20]. Hamstring strength asymmetry has been associated with increased injury risk in football [21]. In one investigation, professional football players with untreated pre-season strength asymmetries were 4.66 times more likely to sustain an HSI [22]; however, systematic reviews report inconsistent findings regarding the association [8,23]. Furthermore, a degree of asymmetry may be a normal physiological occurrence within athletes [24] and side-to-side differences of up to 15% are often not associated with a high injury risk in isolation [25]. A single 'snapshot' of asymmetry is indistinguishable from the transient natural fluctuations that occur with frequent football exposure [20,23,25]. Therefore, a longitudinal analysis is required to establish the reliability of inter-limb strength asymmetry and subsequently evaluate its association with injury risk [20,23,25]. In sports science and medicine (SSM) practice, typical metrics used to evaluate eccentric hamstring strength are peak force and asymmetry in inter-limb strength [8,19].

Player workload management is challenging in English non-league football (NLF; tiers 5–6), where professional and semi-professional teams compete with limited sports science and medical support [26]. Professional NLF players perform less high-speed running than their Premier League (PL) and English Football League (EFL) counterparts [27]; however, it is unknown whether this influences risk of HSI at this level. Furthermore, teams at this level may be full- or part-time, and have varying access to SSM support [27], which may increase a player's injury risk. Existing injury surveillance in English football is limited to the PL and EFL [3,28], and the specific HSI burden in this sub-population of professional NLF male players remains unclear.

This study aimed to develop a predictive model exploring the influence of short-term changes in hamstring eccentric strength and inter-limb asymmetry on HSI risk over the course of a professional NLF season. Additionally, this study aims to compare the predictive value of twice-weekly NHE testing against a traditional baseline testing model.

2. Materials and Methods

2.1. Experimental Design

Using a prospective cohort design, this exploratory study investigated the association of hamstring eccentric strength with HSI incidence in a men's English professional NLF team competing in National League North during the 2019–2020 season. Data collection spanned 36 weeks, covering the pre-season (4 weeks) and competitive season (32 weeks). Players were informed of the study risks and provided written informed consent prior to participation. The study was granted ethical approval by Birmingham City University Ethics Committee (3439).

2.2. Participants

Twenty-four full-time outfield players were recruited from one team. No a priori power calculation was feasible. Inclusion criteria were: (a) age $\geq$ 18 years; (b) held a professional contract; (c) uninjured at study enrolment; and (d) compliant with the NHE testing protocol. Exclusion criteria comprised goalkeepers due to the different physical demands experienced, players on trial, those who sustained an HSI before starting the NHE testing protocol, or those with limited engagement (<4 test days). Participants were familiarised with the testing protocols prior to the start of the study. A typical one-matchday week consisted of four training sessions (duration $\approx$ 60–120 min), and 1–2 gym-based sessions led by the club strength and conditioning coach, which did not include the NHE.

2.3. Data Collection

2.3.1. Injury Surveillance

Following the football consensus statement [29], injury definitions and data collection procedures were applied in this study. A time loss injury was defined "injury that results in a player being unable to fully participate in football training or match play". A player was considered recovered when they returned to full unrestricted training. Injury recurrence was defined as the same injury type at the same site. Injury data were recorded prospectively by the club's sports therapist, present on all match and training days. Standardised injury reports were completed at occurrence and updated as necessary. The researcher, a chartered physiotherapist, audited data collection weekly to ensure consistent reporting of injury data. All clinical diagnoses of time loss HSI, including reinjuries, were included in the analysis; hamstring tendinopathies were not included.

2.3.2. Hamstring Strength Testing

Eccentric hamstring strength was measured as force via strain gauges on a NordBord (VALD Performance, Newstead, Australia), sampling at 50 Hz. Testing occurred twice weekly at the same time of day ($\pm$1 h) prior to training on Monday (~40 h post-match) and Friday (~30 h pre-match) during a standard Saturday match week. During weeks with varied match schedules, testing days were adjusted to maintain similar pre- and post-match timepoints where scheduling permitted. Adherence was constrained by training schedules and compliance, as well as the number of valid tests completed within a player's at-risk window. Testing was integrated into the team's training schedule, and subjective muscle soreness did not preclude testing unless accompanied by a clinical diagnosis restricting training participation. If a player sustained an injury, NHE testing was suspended until full participation was resumed. Missing tests were imputed using last observation carried forward (LOCF).

A standardised warm-up was performed prior to each test: one set of 10 repetitions of leg swings, split squats, bilateral and unilateral bridges, followed by 3 submaximal NHE repetitions ($\leq$4 modified Borg scale), interspersed with a 2 min passive recovery.

For each NHE test, players began by kneeling upright on the padded board. The ankle hooks were placed superior to the lateral malleolus with strain cells perpendicular to the NordBord. Players were instructed to maintain trunk and hip alignment throughout the NHE, with their arms positioned across their chest. Only the eccentric portion of the NHE was performed, and players used their arms to break their fall if unable to control the movement. On each test day, players completed 3 maximal NHE repetitions, instructed to perform the movement as slowly as possible, resisting with both limbs [30]. Strong verbal encouragement was provided during each attempt to ensure maximal effort. The researcher that supervised data collection and analysed all data, and the club's sports therapist were not blinded to players' injury status or NHE data.

2.3.3. Hamstring Strength Metrics

Raw force data from the NordBord was used to calculate bilateral peak force and inter-limb strength asymmetry (Equations (1) and (2)). Analysis was restricted to bilateral peak force and inter-limb strength asymmetry, as these are the most commonly reported metrics within the literature [8,18,19] and provide interpretable Nordbord variables in football settings. Average peak force across three attempts from the right (R) and left (L) limbs were used for analysis. Inter-limb strength asymmetry [31] was calculated as the absolute difference between limbs to assess the magnitude of imbalance, irrespective of stronger limb. Players' standardised z-scores were calculated across the season for each metric, computed as the test score minus the season mean, divided by the season standard deviation (SD). Each unit therefore represents one within-player SD above or below the typical season value, and are presented graphically to demonstrate individual variance over time. These z-scores were used descriptively and not used as predictors, as they require knowledge of each player's full season distribution.

$$bilateral\ peak\ force\ (N{\cdot}kg^{-1}) = \left(\frac{R\ peak\ force + L\ peak\ force}{2}\right) \div BW \quad (1)$$

$$inter-limb\ strength\ asymmetry\ (\%) = \frac{|R\ peak\ force - L\ peak\ force|}{(R\ peak\ force + L\ peak\ force)} * 100 \quad (2)$$

2.4. Statistical Analysis

All data analysis was completed in R v4.4.2 (Vienna, Austria) using the 'survival' package (v3.8.3) and followed TRIPOD guidelines [32]. Data were fully de-identified prior to analysis (player_id only). Subsequent analyses were conducted prospectively using coded data to reduce differential bias. A post hoc minimal detectable effect size (MDES) was calculated for each Cox model, using a formula for a continuous covariate [33]. The bilateral peak force time-varying model and baseline model had 80% power to detect a protective hazard ratio (HR) of 0.29 and 0.2, respectively; the inter-limb asymmetry models had 80% power to detect HR for increased risk of 1.34 and 1.63, respectively.

Descriptive statistics (mean ± SD) and testing compliance were analysed across the study period. Normality was assessed via Shapiro–Wilk test for each group and predictor variable. Non-injured and injured groups were compared using independent two sample t-test and Hedges' g. Data from both variables were screened for outliers, defined as >3 SD from the group mean; group means and SDs were recalculated following the removal of outliers (see Supplementary Materials for full details).

2.5. Predictor Variable Reliability

2.5.1. Within-Session Reliability

Data from the first four test days of the competitive season were analysed. For each limb, the coefficient of variation (CV) and typical error (TE) were calculated from the three repetitions of each test day. Absolute agreement across the three NHE repetitions was assessed using two-way mixed effects intraclass correlation coefficient (ICC [3,1]).

2.5.2. In-Season Variability and Inter-Limb Agreement

Within-player CV for each limb were assessed across the season. Agreement between left- and right-limb CVs was examined using a Bland–Altman analysis.

2.5.3. Between-Session Reliability

Season average reliability for bilateral peak force and inter-limb strength asymmetry was assessed using a two-way random effects model [34]. This model used random intercepts for player and date. The reliability of a single measurement (ICC(A,1)) and of the mean of a player's measurements (ICC(A,k)) were calculated across the season. The absolute reliability was quantified as the TE and the minimal detectable change (MDC_{95}). The cohort's pooled within-subject CV quantified overall variability (see Supplementary Materials for full details).

2.6. Predictive Modelling of Hamstring Injury Risk

2.6.1. Primary Time-Varying Cox Model

A marginal Cox proportional hazards (PH) model using an Andersen–Gill counting process examined the association between time-varying predictors and HSI [35]. This approach allows each player to be at risk of multiple events over the study period. Analyses were limited to univariate models due to the low anticipated event count to avoid overfitting when the number of HSI per model parameter is small. Player-level clustering with robust standard errors was used to account for within-player correlations [36], which was chosen over shared frailty to preserve model stability. The covariates were updated using an LOCF approach, carrying forward a measurement for two days. A measurement was considered representative of a player's neuromuscular fatigue state for the test day and the subsequent 2 days (e.g., MD − 1, MD, and MD + 1). This window aligns with established windows of neuromuscular fatigue, where eccentric strength impairments may last for ~48–72 h following competitive match-play [12–15]. After this 2-day period, the covariate was treated as missing until the next test. For the time-to-event analysis, a player's entry was their first test day. Right censoring occurred at the end of the study or the withdrawal of a participant. Exposure was temporarily suspended when a player was unavailable due to a non-hamstring injury, and re-entered the risk set and monitoring procedures when resuming full training. The Efron method was used to handle tied event times. Due to the limited number of events per variable (EPV), the results should be treated as exploratory (see Supplementary Materials for full details).

2.6.2. Comparative Model: Baseline Cox Model

The baseline model utilised a static predictor for eccentric hamstring strength, calculated from the average of 4 test days before the first competitive match. This method allowed players a five-session familiarisation period and reduced the influence of single session's variability [37].

2.6.3. Model Specification and Validation

Cox PH models were fitted to calculate the Hazard Ratio (HR) and 95% confidence intervals (CI). The HR represents the change in risk of HIS per unit increase in the predictor. Baseline survival probability (S_0) was estimated at 255 days (end of study period), which represents the estimated probability of a player with mean covariate values remaining injury free up to 255 days. The proportional hazards assumption was assessed via Schoenfeld residuals [38]. Model performance assessed for discrimination (the ability to distinguish between events and non-events) using Harrell's C-index (concordance), overall fit using the Akaike Information Criterion (AIC), and calibration via graphical checks of predicted versus observed survival probability using Kaplan–Meier estimates [32,39]. The C-index values were interpreted on established ranges: 0.80–0.89 excellent, 0.70–0.79 acceptable, and <0.70 poor [40]. To explore for potential bias and model stability, performance was also assessed on a subset of the data (start to midpoint of study; see Supplementary Materials for full details).

2.6.4. Sensitivity Analysis

Sensitivity analysis assessed the impact outliers and data handling choices on the primary time-varying model, through unrestricted LOCF imputation and the removal of outliers and those with sparse data (<10 tests).

3. Results

Of the twenty-four players, one player declined to participate and withdrew from the study. Three players were excluded based on pre-defined criteria: sustaining an HSI prior to first test day (n = 1), and players with limited engagement (<4 test days; n = 2). The study sample consisted of twenty outfield players (age: 23.9 ± 4.4 years; height: 1.80 ± 0.09 m; body mass: 78.7 ± 8.4 kg). For the predictive modelling, sample sizes varied by analysis type. The time-varying bilateral peak force model included the full sample (n = 20), whereas the inter-limb strength asymmetry model excluded one outlier (n = 19). The baseline models were restricted to players present at the start of the monitoring period, resulting in samples of n = 14 (bilateral peak force) and n = 13 (inter-limb strength asymmetry), also excluding the asymmetry outlier. A total of 60 separate test days occurred in the study period.

3.1. Hamstring Strain Injury Incidence

Total football exposure time was 2451 h (match exposure: 788 h; training exposure: 1663 h). There were nine HSIs (29% of 31 total injuries, n = 7 players, age: 25.1 ± 3.4 years) recorded across the 36-week period, with incidence rate of 3.67 injuries per 1000 h (95% CI: 1.68–7.02) and burden of 35.49 days per 1000 h (95% CI: 15.54–65.58). Four players disclosed a history of HSI at study enrolment, three of whom sustained an HSI during the study. Two HSIs were reinjuries that occurred in two players.

3.2. Hamstring Strength Profiles

Over the season, bilateral peak force averaged 5.08 ± 0.64 $N \cdot kg^{-1}$. A key finding was that players who sustained an HSI (age: 25.5 ± 3.9 years) had a significantly lower bilateral peak force (mean difference: 0.80 $N \cdot kg^{-1}$, p = 0.027) than their non-injured counterparts (age: 23.2 ± 4.6 years). This corresponds to approximately 15% lower relative bilateral peak force in the injured group, with a large between-group effect size (g = −1.47); detailed output is contained in Table 1. In contrast, inter-limb strength asymmetry, which averaged 4.49 ± 1.94%, showed no difference between injured and non-injured groups (g = 0.38, p = 0.58). Weekly standardised z-scores for both metrics are displayed in Figures 1

and 2. These figures represent the most recent within-player strength metric *z*-score, with colour gradient representing the change per SD from their season mean. Visual inspection of Figure 1 indicates that HSIs were common among players with a lower season-average bilateral peak force. In contrast, Figure 2 demonstrates no systematic pattern between HSI occurrence and asymmetry fluctuations.

Table 1. The season-average hamstring strength outcomes of player groups.

Variable	Group	n	Mean ± SD	95% CI of Mean
Bilateral peak force	Full cohort	20	5.08 ± 0.64 N·kg^{-1}	4.78 to 5.38 N·kg^{-1}
	Non-injured	14	**5.32 ± 0.47N·kg^{-1}**	5.05 to 5.59 N·kg^{-1}
	Injured	6	**4.52 ± 0.64N·kg^{-1}**	3.84 to 5.19 N·kg^{-1}
Inter-limb strength asymmetry	Full cohort	19 *	4.49 ± 1.94%	3.55 to 5.42%
	Non-injured	14	4.30 ± 1.82%	3.25 to 5.35%
	Injured	5 *	5.00 ± 2.42%	2.00 to 8.01%

Note: * outlier removed; SD = standard deviation; CI = confidence interval. Bold text = significant difference between injured and non-injured groups; full cohort was not included in inferential comparisons.

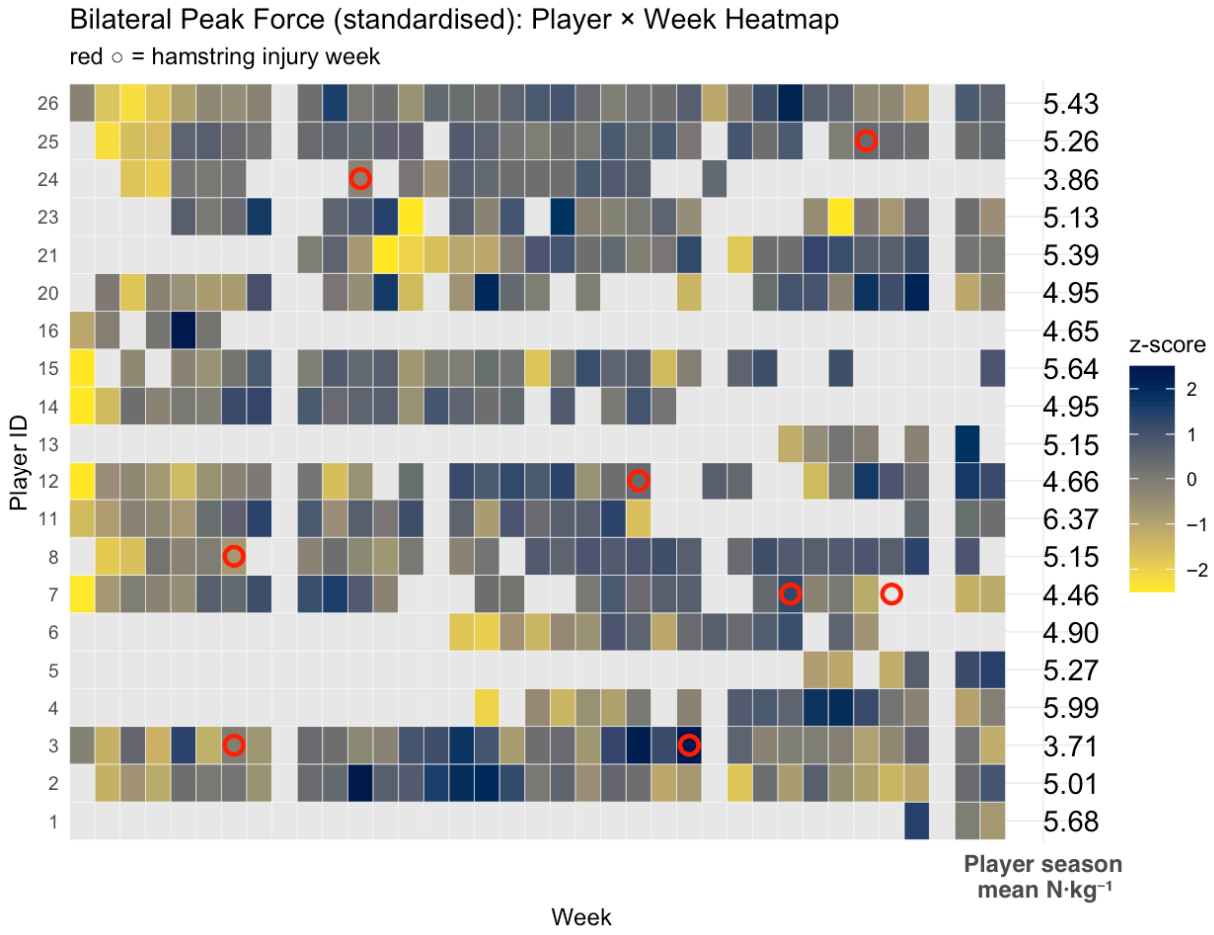


Figure 1. Weekly heatmap of most recent within-player standardised bilateral peak force (*z*-score), with hamstring injury weeks overlaid.

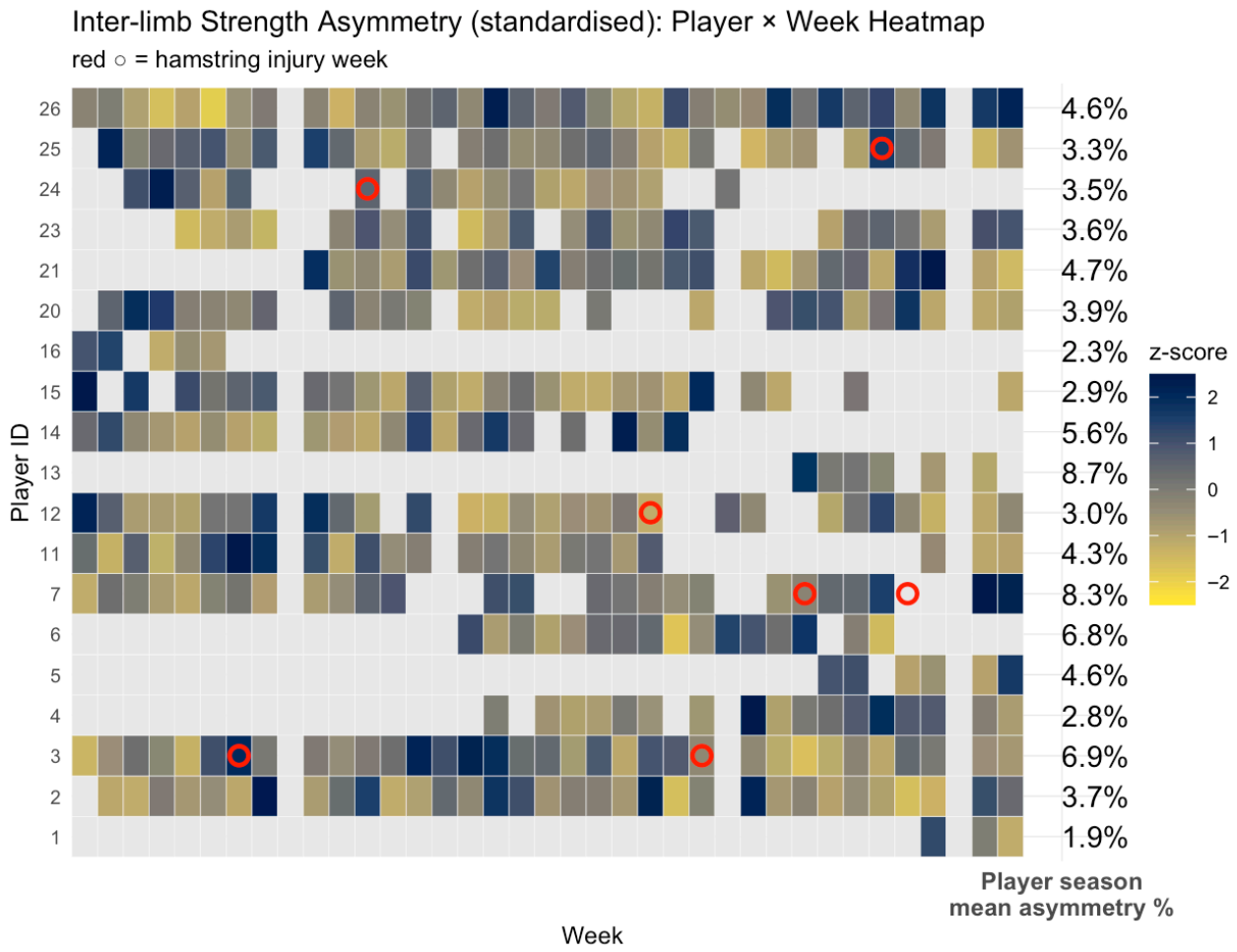


Figure 2. Weekly heatmap of most recent within-player standardised inter-limb strength asymmetry (*z*-score), with hamstring injury weeks overlaid.

Study compliance was high and uniform across groups, averaging 79 ± 20% (34 ± 17 tests per player). All data were confirmed to be normally distributed when assessed via Shapiro–Wilk ($p > 0.05$). One player exhibited notably higher inter-limb strength asymmetry (22.6 ± 5.0%, >9 SD from group mean) and was excluded from asymmetry analysis based on predefined criteria.

3.3. Predictor Variable Reliability

3.3.1. Within-Session Reliability

Across the first two competitive weeks (mean 3.6 ± 0.7 tests per player; $n = 13$), the pooled within-session CV was 9.9% (TE = 25.98 N) for the right limb and 10.6% (TE = 28.06 N) for the left. The agreement across the three repetitions was excellent: ICC(3,1) = 0.93 (95% CI: 0.887–0.957) for the right limb, and ICC(3,1) = 0.93 (95% CI: 0.887–0.959) for the left.

3.3.2. In-Season Variability and Inter-Limb Agreement

Across all test sessions, the within-player CV averaged 10.3 ± 4.3% for the right limb and 9.8 ± 3.4% for the left. The Bland–Altman analysis of limb CVs demonstrated a mean bias of −0.5% (SD 4.2%), with 95% limit of agreement −8.8% to 7.8% (Figure 3).

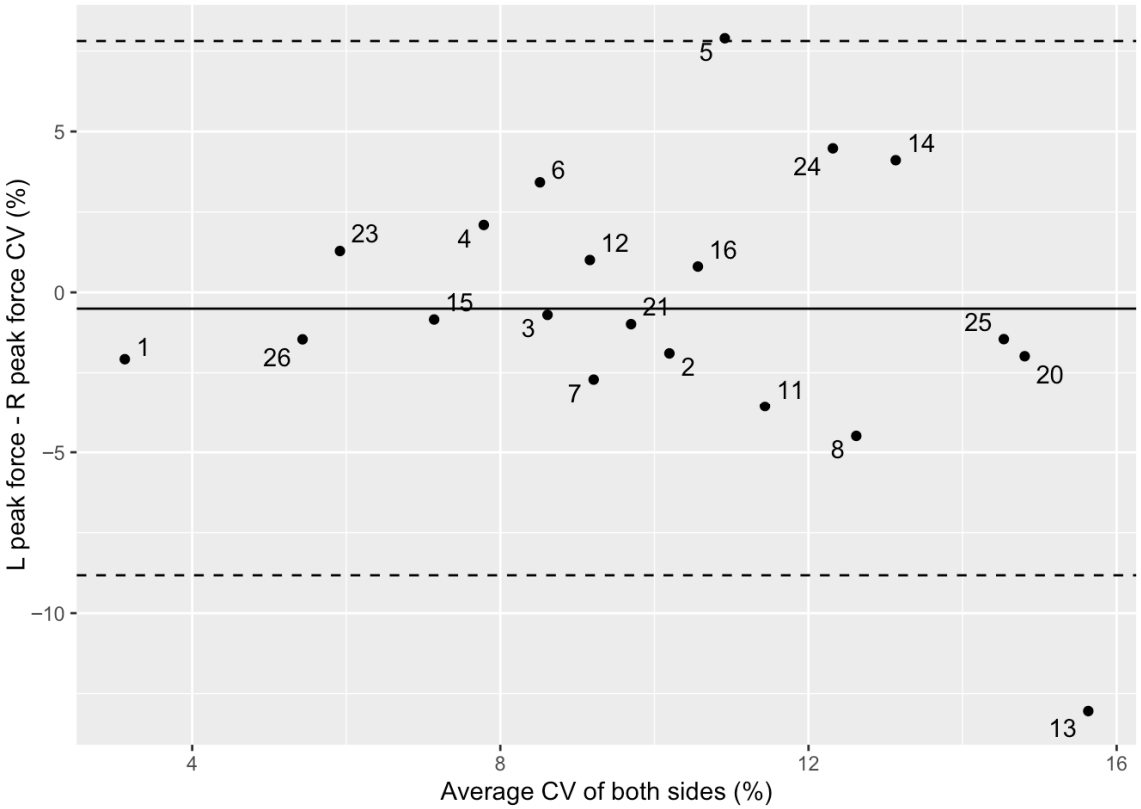


Figure 3. Bland–Altman plot comparing the reliability (CV) of left vs. right leg peak force measurements. Note: Solid line represents the mean bias; dashed lines represent 95% limits of agreement. Data labels indicate individual player_id.

3.3.3. Between-Session Reliability

Bilateral peak force (n = 20) demonstrated moderate within-player variability, with a pooled CV of 9.1% (IQR 6.86–11.5%). The reliability of a single test was poor to good (ICC(A,1) = 0.60, 95% CI: 0.58–0.66), with a TE of 0.43 N·kg^{-1} (MDC$_{95}$ = 1.20 N·kg^{-1}). The season-average reliability across the mean of each player's tests (k = 35) was excellent (ICC(A,k) = 0.98, 95% CI: 0.98–0.99).

Inter-limb strength asymmetry (n = 19) showed high within-player variability across the season, with a pooled CV of 69.3% (IQR 62.6–85.5%). As the between-session variance component was zero, the reliability of a single test was poor (ICC(1,1) = 0.2, 95% CI: 0.12–0.23), with a TE of 3.31% (MDC$_{95}$ = 9.17%). However, the season-average, across a mean of 34.2 tests per player, demonstrated good to excellent reliability (ICC(1,k) = 0.895, 95% CI: 0.82–0.91).

3.4. Predictive Modelling of Hamstring Injury Risk

The results for the Cox PH models are presented in Table 2. Formal validation of discrimination was attempted through bootstrapping and cross-validation. However, due to the small number of injury events, both procedures failed to converge reliably. Therefore, the presented concordance should be treated as exploratory estimates of model discrimination without optimism correction. The calibration of models was assessed graphically, comparing the mean survival probability and the Kaplan–Meier estimate at 36 weeks (see Supplementary Materials for full details). Baseline models included all eligible players present at the beginning of the study (n = 14).

Table 2. The results of the Cox PH models.

Predictor	Model Type	Sample	Coefficient (β)	Hazard Ratio (95% CI)	MDES	Baseline Survival S_0 (255 d)	*p* (Robust Wald)	C-Index (SE)	AIC
Bilateral peak force ($N \cdot kg^{-1}$)	Time-varying	*n* = 20	−1.235	0.29 (0.15–0.56)	0.29	0.60	**0.0002**	0.776 (0.065)	29.48
	Baseline	*n* = 14	−1.617	0.20 (0.09–0.46)	0.20	0.66	**0.0001**	0.824 (0.055)	34.64
Inter-limb strength asymmetry (%)	Time-varying	*n* = 19 *	0.094	1.10 (0.95–1.27)	1.34	0.53	0.216	0.612 (0.119)	27.08
	Baseline	*n* = 13 *	0.065	1.07 (0.79–1.44)	1.63	0.55	0.666	0.527 (0.108)	36.13

Note: * outlier removed from sample. β = regression coefficient. d = days. Hazard Ratio (HR) indicates the multiplicative change in injury risk per unit increase in the predictor. CI = confidence interval. MDES = post hoc minimal detectable effect size (calculated at 80% power). S0 (255 d) = Baseline survival probability; representing the estimated probability of a player remaining injury free up to 255 days (end of study period) with mean covariate values. P = robust Wald statistic. C-index = Harrell's concordance index (measure of the model's ability to distinguish between injured and non-injured players). SE = standard error. AIC = Akaike Information Criterion. Bold values indicate statistical significance ($p < 0.05$).

3.4.1. Bilateral Peak Force as a Predictor of HSI

Bilateral peak force demonstrated a strong and significant protective association with HSI. The time-varying model (observations = 2055; events = 7) demonstrated that a 1 $N \cdot kg^{-1}$ increase in relative bilateral peak force, reduced the hazard of sustaining an HSI by 71% with acceptable discrimination. The baseline model (observations = 3061; events = 8) found a similar protective effect for every 1 $N \cdot kg^{-1}$ increase in relative bilateral peak force, reducing the hazard by 80% with excellent discrimination.

Both time-varying and baseline models met the proportional hazards assumption ($p > 0.05$) and identified a similar protective effect, but their performance over time differed. The time-varying model's bias increased from +0.198 at day 150 to +0.228 by day 160, by which point over half of all HSIs had occurred. In contrast, the bias of the baseline model was more stable, increasing from −0.038 to −0.068 in the same period. However, the AIC indicated the time-varying model had superior fit relative to the data despite its instability.

The predicted survival probabilities for players with low (25th percentile) versus high (75th percentile) bilateral peak force with 95% CI from both models are displayed in Figure 4. Visual inspection of the CI reveals some overlap, reinforcing the finding that while the protective effect is strong, the precision of the estimates is constrained by the sample size. For both time-varying and baseline models, the 95% CIs for the HR extend beyond the MDES, suggesting the study was underpowered to distinguish between moderate and large effects.

The protective association between bilateral peak force and HSI risk proved robust, remaining consistent across sensitivity analyses that tested the LOCF data imputation, players with sparse data, and influence of outliers (see Supplementary Materials for details). The first sensitivity analysis removed the timeframe restriction on LOCF, and all missing data were filled; the association with borderline significance and protective association remained (HR = 0.703, 95% CI: 0.494–1.003, $p = 0.052$; C-index = 0.764, SE = 0.56). Removing players with greater SEM and lower tests (n = 4 with <10 tests, including both outliers from Figure 3) did not meaningfully alter the association, with a significant protective effect remaining (HR = 0.294, 95% CI: 0.153–0.566, $p < 0.001$; C-index = 0.773, SE = 0.068). The protective effect of higher eccentric hamstring strength remained when the asymmetry outlier was removed (HR = 0.3152, 95% CI: 0.143–0.695, $p = 0.004$). All checks satisfied the proportional hazards assumption ($p > 0.05$).

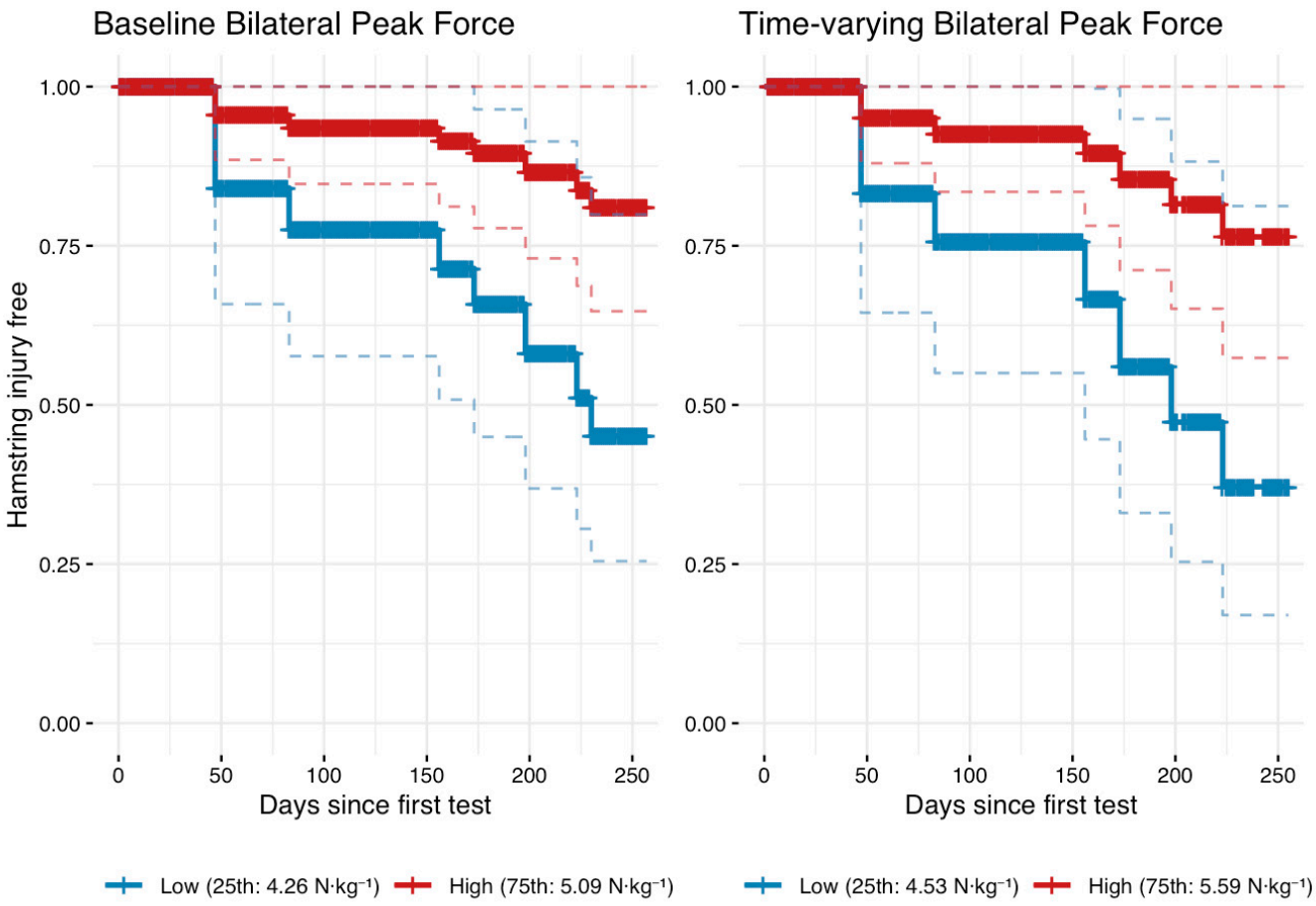


Figure 4. Kaplan–Meier plots of 25th and 75th percentile for baseline and time-varying bilateral peak force models with corresponding dashed lines representing 95% confidence intervals.

3.4.2. Inter-Limb Strength Asymmetry as a Predictor of HSI

Inter-limb strength asymmetry was not a predictor of HSI in either the time-varying (observations = 2055; events = 7) or baseline (observations = 2815; events = 7) models. An initial significant finding in the time-varying model was dependent on a single influential outlier; upon its removal, the effect was nullified (HR = 1.10, 95% CI: 0.95–1.27). The baseline model similarly showed no association with injury risk (HR = 1.07, 95% CI: 0.79–1.44). Both final models satisfied the proportional hazards assumption ($p > 0.05$). Furthermore, the study was not sensitive enough to detect such a small effect, as the observed HRs were below the MDES.

4. Discussion

The primary aim of this study was to determine if an exploratory model using twice-weekly NHE strength data could predict HSI risk, and compare the performance against a baseline model. Given the significant burden of HSI in this NLF cohort (29% of all injuries), identifying valid predictors of injury is important. The primary finding of this exploratory study was that while greater bilateral eccentric peak force was significantly associated with lower HSI risk in both models, the assumption that higher-frequency monitoring would improve prediction was not supported. In contrast, inter-limb strength asymmetry was not associated with HSI risk. This finding may be supported by the poor single-test reliability of asymmetry (ICC(1,1) = 0.2), compared to the moderate reliability of bilateral peak force (ICC(A,1) = 0.6).

The prevalence of HSI in this professional NLF cohort was high (29%). This proportion is substantially higher than the typical values, which range from 12% to 16.5% in professional or semi-professional football [3,28,41]. This study's findings are more comparable to the prevalence of HSI in elite UEFA clubs, which were recently reported at 24% of all injuries [2]. This high rate of HSIs may reflect the unique demands of NLF. For example, in our previous work, one professional NLF team demonstrated lower volumes of high-speed running in matches compared to other professional teams [27], and a lack of exposure to high-speed running has been identified as a potential risk factor for HSI [17,42]. Furthermore, NLF teams often have limited sports science and medicine resources compared to professional levels [26]. This may limit the delivery of preventative strength and conditioning programmes, such as resistance training, speed development, and plyometrics [43], associated with reduced HSI rates [17]. Therefore, priority should be given to the tests that provide the most valuable insight into strength deficiencies linked to injury risk, so resources can be allocated appropriately [44].

In this cohort, greater bilateral peak force was protective against HSI: each 1 $N \cdot kg^{-1}$ increase, a change of approximately 1.5 SD of the full cohort mean, reduced HSI risk by approximately 70–80%. Practically, this implies that even an increase of 0.5 $N \cdot kg^{-1}$ is associated with approximately half the injury risk. This aligns with the findings of Timmins et al. [7], where a seasonal mean greater than 337 N (≈4.38 $N \cdot kg^{-1}$) was also protective. Consistent with the Cox models, the descriptive analysis also showed that players who sustained an HSI had a 0.80 $N \cdot kg^{-1}$ lower season average bilateral peak force than non-injured players. The reliability of the NHE testing in the present study supports the utility as a predictive metric. While single-test reliability was moderate, the excellent season-average reliability demonstrates that players have a stable strength profile, despite weekly fluctuations. Furthermore, the MDC_{95} of 1.20 $N \cdot kg^{-1}$ provides a practical in-season threshold for interpreting NHE strength changes accounting for measurement error, alongside real-world fluctuations specific to a competitive football season with changeable weekly demands.

The injury risk model utilising baseline NHE data demonstrated superior predictive performance compared to the time-varying model. This indicates that, within this cohort, pre-season physical capacities better discriminated HSI risk than recent test scores. Several factors may explain this observation. The baseline model benefitted from lower cumulative measurement error, whereas the time-varying model was susceptible to noise and compounded errors across multiple tests. This noise, inherent in repeated measures, may have limited the true predictive value of the time-varying model, which was limited by the small sample size. The baseline model was also strengthened through the inclusion of one additional injury event, which the time-varying model's LOCF window excluded. Finally, the low within-player variance across the study period may have limited the time-varying model's ability to detect meaningful change.

These results contrast with previous research [18], where baseline pre-season screening offered no predictive value for HSI risk, which may reflect methodological differences (e.g., time-to-event analysis) or the wider between-player variance in an NLF cohort. However, the findings should be interpreted with caution. With only eight injury events, the models could not control for confounders (recommended > 10 EPV) [45], such as age, training loads, or injury history. Furthermore, as the confidence intervals for the observed estimates straddled the calculated MDES, the models could not reliably distinguish between moderate and large effects.

This study found that inter-limb strength asymmetry was not associated with HSI risk, a finding likely explained by the metric's poor single-test reliability. This is consistent with previous research, which suggests inter-limb strength asymmetry has limited utility

for predicting injury risk [37]. However, this study provides evidence that the season-average reliability was good to excellent (ICC(1,k) = 0.895), suggesting that players have a stable inter-limb strength asymmetry profile over a season. Consequently, a stable, low-magnitude inter-limb strength asymmetry may represent a benign individual trait, whereas fluctuations from the baseline could represent maladaptation or fatigue, necessitating longitudinal trajectory modelling. This finding provides context for the study by Opar et al. [19], where HSI risk was associated with persistent asymmetries across multiple tests. Therefore, whilst the present data do not support high-frequency asymmetry monitoring for HSI prediction, due to the study's limited sample size and statistical power, the role of persistent inter-limb strength asymmetries cannot be ruled out and requires investigation in larger cohorts.

Finally, these findings have practical applications across football levels. In NLF, where resources are scarce, clubs should consider benchmarking player strength rather than complex surveillance. Conversely, in elite settings (e.g., EFL/PL), while increased monitoring frequency may not improve prediction, it remains valuable for establishing stable player profiles. In this context, high-frequency data may be best utilised to evaluate longitudinal deviations from a player's baseline, aiding practitioners in differentiating potential maladaptive patterns from normal physiological variability.

5. Limitations and Future Directions

The primary limitations of this study are the small sample of one NLF team over a single season, which was shortened due to COVID-19 restrictions. Although this study provides insights into this under-researched competitive level, its external validity is limited due to heterogeneity in training practices across NLF teams. The low number of HSI events constrained the statistical power of the Cox PH models and introduces potential for overfitting. Therefore, the hazard estimates should be interpreted with caution, and a formal assessment of model discrimination and calibration was not possible. Consequently, analysis was restricted to univariate models of bilateral peak force and inter-limb strength asymmetry and could not control for confounders, such as injury history or training load. Additionally, the exclusion of players with insufficient tests or those sustaining an HSI prior to baseline testing may introduce selection bias, potentially attenuating the association between strength and HSI risk. Thus, the associations between bilateral peak force or inter-limb strength asymmetry and HSI risk should be considered exploratory. The reliance on a physical examination by a single assessor and clinical examination alone, while typical of NLF, is a limitation. Furthermore, the handling of missing data using LOCF, while a pragmatic approach in-season, may underestimate variance and introduce bias [46]. Future research should address these limitations by recruiting larger cohorts to build on these exploratory results and validating target interventions to mitigate risk, allowing for more robust statistical analyses, and controlling for confounders through multivariate analyses. Finally, further investigation should extend to additional metrics such as torque, the use of longitudinal trajectory modelling, and the application of within-player standardisation and directional asymmetry analysis.

6. Practical Implications

- Twice-weekly, in-season NHE testing using a NordBord provided no additional benefit over a baseline pre-season testing for identifying HSI risk.
- Pre-season baseline testing was sufficient for identifying players with low eccentric hamstring strength who may be at greater risk of HSI.
- Inter-limb strength asymmetry demonstrated poor single-test reliability and single tests should be interpreted with caution.

- Players exhibit a stable season-average asymmetry profile, suggesting that the periodic profiling of persistent asymmetry holds greater clinical relevance than high-frequency monitoring.

7. Conclusions

This exploratory study was the first to prospectively assess the predictive value of twice-weekly hamstring strength monitoring in a professional NLF cohort. The findings demonstrated that bilateral peak force was a significant predictor of HSI risk and can be effectively identified with pre-season testing. The assumption that higher-frequency in-season monitoring would lead to better injury prediction is not supported by this study's findings. Additionally, neither the time-varying nor baseline inter-limb strength asymmetry models were predictive of HSI risk in this cohort. Therefore, these findings support the use of standardised pre-season testing to identify and address hamstring strength deficits in individual players that may be associated with increased HSI risk.

Supplementary Materials: The Supplementary Materials and full R output are available in the Open Science Framework at: https://doi.org/10.17605/OSF.IO/U53DT. The supplementary file contains: outlier removal and data cleaning details; full reliability analysis outputs (CV, ICC, TE); detailed Cox Proportional Hazards model specifications (time-varying and baseline); and sensitivity analyses including unrestricted LOCF and model validation plots.

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Abbreviations

The following abbreviations are used in this manuscript:

HSI	Hamstring strain injury
NLF	Non-league football
SSM	Sports science and medicine
NHE	Nordic hamstring exercise
BW	Body weight
MD	Matchday
LOCF	Last observation carried forward
CV	Coefficient of variation
TE	Typical error
ICC	Intraclass correlation coefficient
MDC_{95}	Minimal detectable change at 95% confidence
MDES	Minimal detectable effect size
PH	Proportional hazards

HR	Hazard ratio
EPV	Events per variable
AIC	Akaike Information Criterion
C-index	Concordance index (Harrell's)
CI	Confidence interval
SE	Standard error
SEM	Standard error of measurement

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