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Cameron Lord
Edith Cowan University

Fadi Ma'ayah
Edith Cowan University

Anthony J. Blazevich
Edith Cowan University

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ORIGINAL ARTICLE

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Change in knee flexor torque after fatiguing exercise identifies previous hamstring injury in football players

C. Lord | **F. Ma'ayah** | **A. J. Blazevich**

Centre for Exercise and Sport Science Research (CESSR), School of Medical and Health Sciences, Edith Cowan University, Joondalup, WA, Australia

Correspondence
Cameron Lord, Centre for Exercise and Sport Science Research (CESSR), School of Medical and Health Sciences, Edith Cowan University, Joondalup, WA, Australia.
Email: clord0@our.ecu.edu.au

Muscular fatigue and interlimb strength asymmetry are factors known to influence hamstring injury risk; however, limb-specific exacerbation of knee flexor (hamstrings) torque production after fatiguing exercise has previously been ignored. To investigate changes in muscular force production before and after sport-specific (repeated-sprint) and non-specific (knee extension-flexion) fatiguing exercise, and explore the sensitivity and specificity of isokinetic endurance (ie, muscle-specific) and single-leg vertical jump (ie, whole limb) tests to identify previous hamstring injury. Twenty Western Australia State League footballers with previous unilateral hamstring injury and 20 players without participated. Peak concentric knee extensor and flexor ($180°\bullet s^{-1}$) torques were assessed throughout an isokinetic endurance test, which was then repeated alongside a single-leg vertical jump test before and after maximal repeated-sprint exercise. Greater reductions in isokinetic knee flexor torque (−16%) and the concentric hamstring:quadriceps peak torque ratio (−15%) were observed after repeated-sprint running only in the injured (kicking) leg and only in the previously injured subjects. Changes in (1) peak knee flexor torque after repeated-sprint exercise, and (2) the decline in knee flexor torque during the isokinetic endurance test measured after repeated-sprint exercise, correctly identified the injured legs (N = 20) within the cohort (N = 80) with 100% specificity and sensitivity. Decreases in peak knee flexor torque and the knee flexor torque during an isokinetic endurance test after repeated-sprint exercise identified previous hamstring injury with 100% accuracy. Changes in knee flexor torque, but not SLVJ, should be tested to determine its prospective ability to predict hamstring injury in competitive football players.

KEYWORDS
asymmetry, fatigue, hamstring strain, injury identification, inter-limb, kicking leg

1 | INTRODUCTION

Hamstring injuries comprise 12%-16% of all injuries in football. They are recognized as the most frequently injured muscle group, accounting for more lost time due to injury than any other muscle group.[1-6] These injuries can be long-standing, and injured players are prone to injury recurrence even after rehabilitation; the re-injury rate for hamstrings has been reported to be 12%-31%.[2,5,7-9] While muscular fatigue and interlimb strength imbalances are believed by practitioners to influence hamstring injury risk,[10-13] it is rarely documented whether the weaker leg might also fatigue faster during intense running activities and whether this may increase injury risk. Moreover, while most footballers exhibit limb dominance during kicking (ie, they have a preferred and non-preferred kicking leg), it is not known whether this preference is a predisposing factor for hamstring injuries[14] because little research has attempted to discriminate between kicking and non-kicking legs while investigating hamstring injury.[5,9,15,16]

A first step in understanding these possible effects is to determine whether fatigue-induced hamstrings strengths differ between limbs and between previously injured and uninjured footballers, that is, whether the injured limb fatigues more rapidly. Furthermore, it is of interest to determine (1) whether fatigue induced through football-specific running tasks influences limb-specific fatigue differently to targeted exercises such as cyclic knee extension-flexion movements, and (2) whether muscle-specific (knee flexor) weakness is more or less closely associated with hamstring injury than global (ie, whole lower limb) fatigue. Therefore, the purposes of this study were to quantify (a) differences in knee flexor (hamstrings) force production, and (b) resulting fatigue responses in the knee flexors and whole limb, of the kicking and non-kicking legs in previously injured and uninjured footballers. Subsequently, the sensitivity and specificity with which test results could correctly classify previously injured and uninjured legs were assessed using binary logistic regression.

2 | METHODS

2.1 | Subjects

Forty footballers currently playing in the Western Australia State League (semi-professional level) volunteered for the study. All footballers had at least 2 years of State League playing experience and had been playing football for at least 5 years. The subjects were assigned to either an injured (IG) or uninjured group (UG) based on the following criteria: (a) injury history of one or multiple hamstring injuries to 1 leg only (a unilateral hamstring injury) **as** reported by a clinical physiotherapist; (b) the injury caused the athlete to miss at least 1 week of training (6 ± 2 week; the injury was significant); (c) the injury occurred less than 2 years prior to testing (13 ± 4 month; the injury was sufficiently recent); but (d) the subject was currently "injury free" and playing competitive football; testing was conducted in-season. The ethical approval for the study was granted by the university's Human Research Ethics Committee (ID9302).

After 2 familiarization sessions, during which the single-leg vertical jump (SLVJ), isokinetic endurance test (IET) and repeated-sprint (RST) test were practiced (described below), testing was performed over 3 sessions each separated by 1 week and conducted at the same time of day. The subjects were asked to record and maintain a normal diet (including fluid ingestion) and refrain from performing strenuous exercise for 48 hours prior to testing. Before the commencement of testing, a 5-minute warm-up on a non-motorized treadmill (Curve Treadmill Dynamometer, Woodway, Waukesha, Wisconsin) at 2 m s^{-1} (ie, jog) was completed and the subjects were given the opportunity to perform dynamic stretches for a total of 2 minutes. The exact pretesting protocol was recorded and then repeated in subsequent sessions. Once the warm-up was completed, the subjects followed 1 of 3 testing protocols in a randomized order (but starting with either Test Protocol 1 or 3), as described below.

2.2 | Test protocol 1: Isokinetic endurance test (IET; non-fatigued condition)

The subjects were seated on an isokinetic dynamometer (System 3; Biodex Medical Systems, Shirley, NY) with a hip joint angle of 85° (0° = full extension), diagonal straps secured across the chest, and a seatbelt applied across the hips. The dynamometer was set to allow contractions at an angular velocity of 180° s^{-1} through a 90° knee angle. This speed was chosen because the higher-speed movement more closely replicates the force-velocity requirements of athletic movements and ensures that fatigue mechanisms influencing both force and velocity components could influence performance.[17] The order of testing was randomized between legs.

The subjects performed 50 consecutive maximal concentric knee extension and flexion contractions with the instruction to exert the greatest force possible during the test. A criterion was set that the subjects would repeat the test if 95% of maximal joint torque was not achieved during the first 5 repetitions, but this did not occur. The opposite leg was then tested after a 2-minute rest. The loss of knee flexor and extensor maximal torque were measured over the 50 repetitions, with the decline in peak knee extensor and flexor torque production compared between muscle groups (hamstring and quadriceps) of the same leg and between legs.[18] The concentric hamstring:quadriceps ratio (H:Q) was calculated as peak flexor torque divided by peak extensor torque.[19] Furthermore, the declines in knee flexor and extensor torque production (as a percentage; $-\Delta\%Q$ and $-\Delta\%H$, respectively) over 50 contractions were calculated as: $-\Delta\% = ([MT_{1\text{-}5}\text{-}MT_{46\text{-}50}]/MT_{1\text{-}5})\times 100$, where $MT_{1\text{-}5}$ represents the mean torque of the 1st to 5th repetitions and $MT_{46\text{-}50}$ represent the mean torque of the 46th-50th repetitions.[18] The subjects were not informed of results during testing to prevent feedback effects. The eccentric hamstring:quadriceps ratio was not calculated to limit the risk of muscle soreness in players while they were in-season.

2.3 | Test protocol 2: Repeated-sprint endurance test (RST; fatigued condition)

Subjects completed a repeated-sprint test (RST) before completing an IET (described above). As repeated sprints are prominent in football, the RST was utilized to induce acute neuromuscular fatigue using a movement task that is commonly performed by the subjects but evokes whole limb (rather than hamstring-specific) fatigue.[20] After completing their warm-up, a RST was completed on a non-motorized treadmill consisting of ten 6-second maximal running bouts with 24 seconds of active recovery (jogging at 2 m s^{-1}) between each sprint. The subjects were instructed to build to their maximum velocity as quickly as possible, and the acceleration phase of the sprint was included in the 6-s sprint data collection period. Feedback of running speed and time was provided by the Pacer Performance System software (Innervations Solutions, Joondalup, Australia). The subjects were given verbal encouragement to perform maximally throughout the repeated sprints.

After 3 minutes of passive recovery, the subjects performed an IET using the protocol outlined in Test Protocol 1. The torque decrement measured during the 50 concentric contractions in the second test session (Test Protocol 2) was compared to Test Protocol 1 in the first session (non-fatigued IET for both legs) with the comparison between the pre-RST and post-RST conditions used as a measure of "fatigue." That is, the effect of the RST on fatigue measured during the IET was determined from the combined results of Test Protocols 1 and 2.

2.4 | Test protocol 3: Single-leg vertical jump test (SLVJ; non-fatigued and fatigued conditions)

Single-leg vertical jump (SLVJ) tests were performed both before and after a RST to test whole-limb fatigue responses. The subjects stood on 1 leg on a portable force platform (400 Series Performance Plate, Fitness Technology, Adelaide, Australia) and squatted to approximately a 70-80° knee angle (0° = full extension) as quickly as possible and then explosively jumped with maximal effort as high as possible.[21] The SLVJ was performed 3 times on each leg, alternating between kicking and non-kicking legs with a 10-second passive rest between. The subjects kept their hands on their hips to minimize arm contribution and flexed the opposing knee parallel with the ground to help maintain balance during the descent phase of the jump.[21] In the familiarization session, the subjects performed SLVJs on each leg as many times as necessary until they were competent with the technique and proper form was demonstrated. The difference in peak jump force and height measured before and after the RST was used to quantify the magnitude of fatigue, with the mean of the 3 jumps used for analysis. Jump height (JH) was calculated as $\frac{1}{2}g(t/2)^2$, where $g = 9.81$ m s^{-2} and t = flight time.

Three minutes after the first SLVJ test series, the subjects performed a RST as described in Test Protocol 2. The jump tests were then repeated 3 minutes after the completion of the RST (fatigued condition) and the decrement in peak jump force and height from pre- to post-RST was used as an indicator of fatigue.

2.5 | Statistical analysis

The data were analyzed using SPSS statistical software (SPSS 23, Chicago, I11). Means and standard deviations were calculated as measures of centrality and spread of data for all dependent variables. Outcome measures were analyzed using multivariate repeated measures ANOVA, with "leg" (kicking and non-kicking leg) and "time" (before and after the RST) as within-subject variables and "group" (with 2 levels; injured and uninjured) as the between-group factor. Independent *t* tests were performed between groups to assess whether significant differences were detectable between the injured and uninjured groups. Effect sizes (ES) were calculated as the ratio of the mean change to the control group (before RST) standard deviation.[22] Binary logistic regression analysis was performed to determine the probability of subjects falling into "injured" or "uninjured" leg categories. From this analysis, sensitivity (true positive/(true positive+false negative)×100) and specificity (true negative/(true negative+false positive)×100) were calculated. Receiver operating characteristics (ROC) were calculated to assess the area under the curve (AUC) in order to indicate how well the variables under consideration discriminated between previously injured and uninjured legs. An AUC of 1 (100%) represents perfect discrimination for a binary outcome. The point at which the AUC is maximized, and is reflective of the optimal discrimination potential, was considered the value at which a "cutoff" might identify previous injury. Statistical significance was accepted at an alpha level of 0.05.

3 | RESULTS

In all cases, the kicking leg was reported as the injured leg in the injured group.

3.1 | Changes in peak knee extensor and flexor torque

As shown in Table 1, no significant differences were found in the changes in peak knee extensor torques measured in the IET before and after the RST between the kicking (−4%; ES = 0.41) and non-kicking (−3%; ES = 0.29) legs of IG ($P = .17$), or between kicking (−2%; ES = 0.20) and non-kicking (−2%; ES = 0.16) legs of UG ($P = .53$). Furthermore, no significant group×time interaction ($P = .62$) was observed. No significant differences were found in knee flexor torque changes between kicking (−6%; ES = 0.41) and non-kicking (−3%; ES = 0.20) legs in UG ($P = .182$); however, differences were observed between the changes in flexor torques between kicking (−16%; ES = 0.89) and non-kicking (−4%; ES = 0.33) legs in IG ($P = .006$). Similar results were found when the torque changes were measured in the first contraction of the IET before and after the RST (Table S1).

3.2 | Changes in knee extensor and flexor torques during the IET

No significant differences were observed in the percent decline in knee extensor torque (comparing the mean torque

TABLE 1 Mean (± SD), percent changes (pre- to post-RST), effect sizes (ES) and 95% confidence intervals (95% CI) for peak knee extensor and flexor torques and peak concentric hamstring:quadriceps ratio (H:Q) of kicking and non-kicking legs measured in the first 5 repetitions of the isokinetic endurance test (IET)

	Before RST	After RST	% Change	ES (*d*)	95% CI
Knee extensor torque (Nm)					
Injured group					
kicking leg	262.5 ± 22.8	253.1 ± 20.3	-4 ± 3	0.41	5.7-13.2
non-kicking leg	258.6 ± 22.3	252.2 ± 22.4	-3 ± 2	0.29	4.4-8.3
Uninjured group					
kicking leg	240.2 ± 26.2	234.9 ± 25.7	-2 ± 1	0.20	3.9-6.7
non-kicking leg	247.3 ± 26.9	243.1 ± 27.4	-2 ± 1	0.16	2.7-5.8
Knee flexor torque (Nm)					
Injured group					
kicking leg	156.4 ± 28.2	131.9 ± 25.4	-16 ± 4[a,b,c]	0.89	21.5-27.5
non-kicking leg	155.2 ± 20.4	148.5 ± 19.1	-4 ± 1	0.33	5.9-7.6
Uninjured group					
kicking leg	148.7 ± 20.9	140.2 ± 19.3	-6 ± 1	0.41	7.3-9.7
non-kicking leg	151.8 ± 21.8	147.5 ± 21.2	-3 ± 1	0.20	3.7-4.9
Hamstring:Quadriceps (H:Q)					
Injured group					
kicking leg	0.60 ± 0.11	0.52 ± 0.10	15 ± 3[a,b,c]	0.75	0.06-0.11
non-kicking leg	0.60 ± 0.07	0.59 ± 0.07	-2 ± 2	0.07	-0.01-0.02
Uninjured group					
kicking leg	0.62 ± 0.09	0.60 ± 0.08	-3 ± 1	0.15	-0.01-0.02
non-kicking leg	0.61 ± 0.09	0.61 ± 0.09	0 ± 1	0.02	-0.02-0.02

RST, repeated-sprint test.

[a] Significant difference ($P < 0.05$) from pre- to post-RST.

[b] Significant difference ($P < 0.05$) between kicking and non-kicking legs in injured group.

[c] Significant difference ($P < 0.05$) between kicking legs of injured and uninjured groups.

of contractions 46-50 to contractions 1-5 in IET) between the kicking (57%; ES = −1.67) and non-kicking (30%; ES = −1.08) legs of IG ($P = 0.16$), or between kicking (20%; ES = −0.75) and non-kicking (44%; ES = −1.43) legs of UG ($P = .57$), as shown in Table 2. Furthermore, no significant group×time interaction ($P = .354$) was observed in the differences in the percent decline in knee extensor torque. Nonetheless, significant differences ($P < .001$) were observed in the percent decrease in knee flexor torque during the IET between kicking (96%; ES = −5.83) and non-kicking (14%; ES = −1.18) legs in IG, while significant differences were not observed ($P = .14$) in the decline between kicking (5%; ES = −0.92) and non-kicking (7%; ES = −1.28) legs in UG. A significant group×time interaction ($P = .014$) was observed in the differences in percent decline in knee flexor torque of the kicking leg.

3.3 | Changes in H:Q (ratio)

Significant differences ($P = .009$) were found in changes in H:Q between the kicking (−15%; ES = 0.75) and non-kicking (−2%; ES = 0.07) legs in IG, but not between the kicking (−3%; ES = 0.15) and non-kicking (0%; ES = 0.02) legs in UG ($P = .374$), as shown in Table 1. A significant group×time interaction ($P < .001$) was observed between groups in changes in H:Q of the kicking leg only.

3.4 | Changes in peak single-leg jump force (PJF) and height (PJH)

As shown in Table 3, significant differences ($P = .049$) were found for changes in PJF between the kicking (−11%; ES = 1.00) and non-kicking (−5%; ES = 0.43) legs in IG, but not in UG (−6%, ES = 0.49 and −8%, ES =−0.64; $P = .113$). A significant group×time interaction ($P = .043$) was observed for changes in PJF of the kicking leg. Significant differences were observed ($P = .003$) in the changes in PJH between the kicking (−13%; ES = 1.18) and non-kicking (−10%; ES = 0.64) legs in IG, but no differences were found ($P = .113$) between kicking (−6%; ES = 0.37) and non-kicking (−8%; ES = 0.60) legs in UG. A significant group×time interaction ($P = .043$) was observed between groups for the changes in PJH of the kicking leg only.

TABLE 2 Mean (± SD), percent differences (pre- to post-RST), effect sizes (ES) and 95% confidence intervals (95% CI) for the changes in knee extensor and flexor torque (comparing the mean torque of contractions 46-50 to contractions 1-5) in kicking and non-kicking legs during the isokinetic endurance test (IET)

	Before RST	After RST			
	% Decline	% Decline	% Difference	ES (*d*)	95% CI
Decline in knee extensor torque					
Injured group					
preferred leg	-22.7 ± 1.4	-35.7 ± 1.9	57.3 ± 5.5	-1.67	-14.1 to -11.9
non-preferred leg	-19.6 ± 1.3	-25.5 ± 1.8	30.1 ± 5.9	-1.08	-6.8 to -5.1
Uninjured group					
preferred leg	-22.2 ± 2.8	-26.6 ± 1.9	19.8 ± 11.0	-0.75	-5.7 to -2.9
non-preferred leg	-17.6 ± 1.2	-25.4 ± 1.3	44.3 ± 6.5	-1.43	-8.9 to -7.0
Decline in knee flexor torque					
Injured group					
preferred leg	-28.0 ± 5.4	-54.9 ± 18.6	96.0 ± 8.3[a,b,c]	-5.83	-35.2 to -28.7
non-preferred leg	-26.6 ± 3.1	-30.2 ± 2.0	13.5 ± 6.6	-1.18	-4.6 to -2.8
Uninjured group					
preferred leg	-32.0 ± 1.7	-33.6 ± 1.7	5.0 ± 5.0	-0.92	-2.3 to -0.9
non-preferred leg	-24.3 ± 1.4	-26.1 ± 1.3	7.4 ± 4.4	-1.28	-2.5 to -1.5

RST, repeated-sprint test.

[a] Significant difference ($P < 0.05$) between pre- and post-RST.

[b] Significant difference ($P < 0.05$) between kicking and non-kicking legs in injured group.

[c] Significant difference ($P < 0.05$) between kicking legs of injured and uninjured groups.

TABLE 3 Mean (±SD) and percent changes (pre- to post-RST), effect sizes (ES) and 95% confidence intervals (95% CI) in peak jump force and height of preferred and non-preferred kicking legs during the single-leg vertical jump test (SLVJ)

	Before RST	After RST	% Change	ES (*d*)	95% CI
Peak jump force (N)					
Injured group					
kicking leg	3372 ± 370	3000 ± 374	-11 ± 7[a,b,c]	1.00	260-483
non-kicking leg	3907 ± 445	3718 ± 479	-5 ± 4	0.43	118-260
Uninjured group					
kicking leg	3037 ± 354	2863 ± 323	-6 ± 5	0.49	102-246
non-kicking leg	3379 ± 410	3117 ± 381	-8 ± 4	0.64	203-322
Peak jump height (m)					
Injured group					
kicking leg	0.105 ± 0.012	0.091 ± 0.010	-13 ± 7[a,b,c]	1.18	0.011-0.018
non-kicking leg	0.129 ± 0.022	0.116 ± 0.019	-10 ± 4	0.64	0.011-0.017
Uninjured group					
kicking leg	0.095 ± 0.015	0.088 ± 0.016	-6 ± 5	0.37	0.004-0.008
non-kicking leg	0.110 ± 0.015	0.101 ± 0.015	-8 ± 5	0.60	0.006-0.012

RST, repeated-sprint test.

[a] Significant difference ($P < 0.05$) from pre- to post-RST.

[b] Significant difference ($P < 0.05$) between kicking and non-kicking legs in injured group.

[c] Significant difference ($P < 0.05$) between kicking legs of injured and uninjured groups.

3.5 | Identification of hamstring injury

Binary logistic regression analyses were performed to identify the previously injured legs (ie, from 80 total legs) from changes in IET and SLVJ variables before and after RST (Table 4). Changes in the peak knee flexion torque from pre- to post-RST ($P < .001$) and the percent decline in knee flexor torque measured during the IET after RST

($P < .001$) both explained 100% of variance (Nagelkerke R^2) and correctly classified 100% of previously injured and uninjured legs (ie, 100% specificity and sensitivity). Furthermore, these variables demonstrated a perfect AUC of 1 and further illustrate the perfect discrimination of the binary outcome (Table 5). Changes in peak knee flexion torque from contraction 1 of IET before RST to contraction 1 of IET after RST ($P = .001$) explained 88.8% of variance and correctly classified 85% of previously injured legs and 98.3% of uninjured legs. The change in H:Q during the IET after RST ($P = .003$) explained 92.6% of the variance and correctly classified 85% of previously injured legs and 91.7% of uninjured legs ($P = .003$). Changes in PJH and PJF pre- to post-RST explained only 10.4% and 19.9% of the variance and correctly classified 5% and 20% of previously injured legs, respectively.

4 | DISCUSSION

The purpose of this study was to (a) quantify differences in interlimb force production in the kicking and non-kicking legs in previously injured and uninjured footballers, and (b) compare responses between kicking and non-kicking legs in fatigue-related decreases in voluntary knee extensor and flexor torque (H:Q ratio) as well as both force production and jump height measured during a single-leg vertical jump (SLVJ). This allowed for the sensitivity and specificity of identifying previous hamstring injury to be assessed from the functional test data.

The present results provide clear evidence that both knee flexor torque production and the hamstrings:quadriceps ratio (H:Q; measured at $180^{\circ}s^{-1}$) decline more rapidly in previously injured than non-injured legs when measured after

TABLE 4 *P* values (*P*), sensitivity, and specificity for the binary logistic regression analysis for all subjects (injured and uninjured)

	Nagelkerke R^2	P	Sensitivity (%)	Specificity (%)
Changes in PKF pre- to post-RST	1.000	<.001*	100	100
Percent decline in KF post-RST	1.000	<.001*	100	100
Changes in KF pre^1-RST to post^1-RST	0.880	.001*	86	98
Changes in H:Q post-RST	0.926	.003*	85	92
Changes in PJF pre- to post-RST	0.199	.003*	20	95
Changes in PJH pre- to post-RST	0.104	.019*	5	97

H:Q, hamstring:quadriceps ratio; PJF, peak jump force; PJH, peak jump height; PKF, peak knee flexor; Pre^1-RST to post^1-RST, first contraction during IET before and after RST; RST, repeated-sprint test.

*Significant predictors ($P < .05$).

TABLE 5 Area under the curve (AUC), *P* values (*P*), 95% confidence interval (95% CI) and the cutoff point for the receiver operating characteristics (ROC) analysis for all subjects (injured and uninjured)

	AUC	P	95% CI	Cutoff point
Changes in PKF pre- to post-RST	1.000	<.001*	1.000-1.000	-13.1 Nm
Percent decline in KF post-RST	1.000	<.001*	1.000-1.000	40%
Changes in KF pre^1-RST to post^1-RST	0.993	<.001*	0.979-1.000	-12.9 Nm
Changes in H:Q post-RST	0.993	<.001*	0.980-1.000	-0.15
Changes in PJF pre- to post-RST	0.753	.001*	0.625-0.881	-266.4 N
Changes in PJH pre- to post-RST	0.665	.027*	0.521-0.810	-0.01 m

H:Q, hamstring:quadriceps ratio; PJF, peak jump force; PJH, peak jump height; PKF, peak knee flexor; Pre^1-RST to Post^1-RST, first contraction during IET before and after RST; RST, repeated-sprint test.

*Significant predictors ($P < .05$).

repeated-sprint exercise (repeated-sprint test; RST) or during an isokinetic endurance test (IET), even in subjects who had returned to competitive match play. In fact, knee flexor torque decreased 16% from pre- to post-RST in the kicking legs of injured subjects (ie, the kicking leg was always the injured leg), which was 11% greater than the decrease in the non-kicking (non-injured) leg. Furthermore, the decrease in knee flexor torque in the kicking leg measured during the IET only after the RST (−96%) was 65% greater than that observed in the non-kicking (ie, non-injured) leg. Therefore, despite these previously injured players receiving clearance to return to full play after rehabilitation, the current results show that deficiencies still existed in hamstring strength which were clearly visible only after fatiguing exercise and therefore indicates a lack of ability to tolerate high levels of work. Speculation can be made that such deficiencies might contribute to the reported hamstring re-injury rates.[7,8,16]

Similar changes were also observed in the H:Q ratio, and indeed H:Q of previously injured players measured in the fatigued condition was 0.52 in the kicking (ie, injured) leg. If the data of Yeung et al (2009) are correct, that $H:Q < 0.60$ measured at $180°s^{-1}$ is a strong predictor of hamstring injury, then injury (re-injury) risk would be significant in the current cohort after fatiguing exercise (eg, repeated sprints). The increasing asymmetry (−13%) between injured and non-injured legs in this index after fatiguing exercise indicates that this change was specific to previously injured legs. Based on these results, we speculate that important information pertaining to player hamstring injury risk might be obtained by testing changes in knee flexion strength and H:Q after fatiguing exercise.

The present findings suggest that previous injury may have affected knee flexion endurance, particularly in the kicking leg (the injured leg in all cases). These findings are consistent with past observations of reduced knee flexor force development in previously injured individuals (injury within 36 months of the study) even after rehabilitation when compared to the uninjured limb.[23-26] Additionally, previous research has concluded that inadequate eccentric muscle endurance could be associated with an increased risk of recurring hamstring injury.[27] The present data further indicate that interlimb asymmetry is exacerbated after a bout of fatiguing exercise, whether imposed using maximal muscle contractions (ie, IET; not specific to running sports) or using repeated-sprint runs (ie, more sport specific).

To further examine the hypothesis that testing hamstring muscle function in the fatigued condition may be a useful tool for injury identification (or return to play), logistic regression analysis was performed to assess the specificity and sensitivity with which the previously injured legs could be identified from the test data. In this analysis, 100% of previously injured (20 legs) and uninjured legs (60 legs) could be identified using (a) the change in peak knee flexor torque measured from pre- to post-RST, and (b) the percent decline

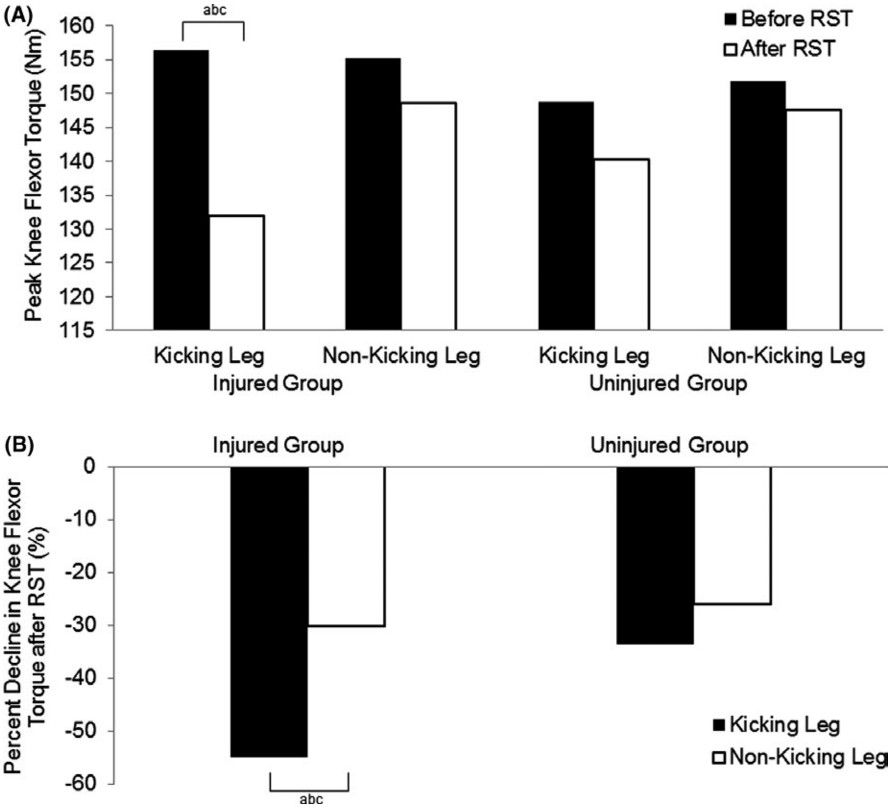

FIGURE 1 Perfectly predicted binary logistic regression analysis of (A) mean changes (pre- to post-RST) in peak knee flexor torque measured in the first 5 repetitions of IET and (B) the decline in knee flexor torque (comparing the mean torque of contractions 46-50 to contractions 1-5) during IET, of kicking and non-kicking legs,[a]Significant difference ($P < .05$) before and after RST. [b]Significant difference ($P < .05$) between kicking and non-kicking legs. [c]Significant difference ($P < .05$) between injured and non-injured groups. RST = Repeated-sprint test. IET = Isokinetic endurance test

in knee flexor torque measured during the IET conducted after the RST (see Figure 1A,B). Additionally, receiver operating characteristics (ROC) analysis demonstrated a perfect area under the curve (AUC = 1) for these variables. This analysis also documented optimal cutoff values for each variable, providing a "score" from the muscle-specific IET which contributed to the perfect discrimination of previous hamstring injury (Table 5). While previous research has found that specific hamstring tests were not strongly predictive of hamstring injury,[28] the results of the present study highlight the value of measuring changes in torque production in a fatigued state. Although the differences were small, changes in knee flexion torque may be marginally better identifiers than the H:Q ratio (see Table 4). However, the effect of hamstring fatigue had greater significance when testing was performed specifically for knee flexion using the isokinetic dynamometer than the single-leg vertical jump test, which is a measure of whole-limb functional performance. This indicates that specific hamstring, but not whole limb, fatigue may be a factor influencing hamstring injury risk and tends to be left deconditioned after return to play. Furthermore, the power of the test to identify previous injury might speculatively indicate that general fatigue-related weakness or loss of structural integrity of the muscle directly predisposes it to injury or that the test might detect individuals whose rapid fatigue responses might exacerbate typical fatigue-related alterations in reflex activation of muscle during lengthening contractions,[29,30] which may increase injury risk. However, further research is required to both replicate the current findings and determine the factors contributing to its power to detect previously injured muscles. Based on the current evidence, these tests might now be examined for their ability to prospectively predict hamstring injury in competitive football players and, potentially, participants in other sports.[31]

In conclusion, the kicking leg was always reported as the injured leg in the present study, and this leg displayed a significant knee flexor fatigue response only in previously injured players, which exacerbated knee flexor torque and H:Q ratio asymmetry. These findings highlight that hamstring "fatigability" of a single limb (ie, asymmetry) may be an important potential risk factor for hamstring injury or re-injury and that players who have returned to competitive match play may still exhibit a marked knee flexor fatigue response to exercise. Furthermore, we found that the previously injured legs of 20 players with and 20 players without previous hamstring injury could be identified with 100% accuracy using the change in peak knee flexor torque from pre- to post-RST (ie, 10 maximal repeated sprints) or the percent decline in knee flexor torque measured during the isokinetic endurance test after a repeated-sprint test. This indicates that changes in hamstring muscle, but not whole-limb (eg, single-leg vertical jump), function in response to exercise-related fatigue may be more important than the absolute values measured either before or after fatiguing exercise for the prediction of hamstring injury.

5 | PERSPECTIVE

This study is the first to examine the identification of previous hamstring injury (ie, retrospective analysis) using muscle-specific and whole-limb test protocols to compare limb-specific force production under fatigued and non-fatigued conditions. The high accuracy (100% sensitivity and specificity, and perfect AUC of 1) of previous hamstring injury identification reported in this study suggests that these tests should be examined prospectively for their ability to predict hamstring injury in football players and other athletes. Future studies may also attempt to use alternate hamstring function tests that might be more useable in situ in the sporting environment; with sufficient evidence, these might also be used in prospective trials. The current study results also highlight the importance of improving hamstring function in both non-fatigued and fatigued conditions before clearing individuals to return to play.

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ORCID

C. Lord http://orcid.org/0000-0002-3024-6680

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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