



Article

Acute Hamstring Fatigue in Elite Male Sixes Lacrosse Players Following a Single Competitive Match

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Abstract

Background/Objectives: Decreases in hamstring isometric strength have been observed post-competition, but research has currently focused only on soccer players. Therefore, the purpose of the present study was to observe if acute reductions in isometric hamstring force production in elite male lacrosse players occur post-match. **Methods:** Peak isometric force measurements were collected from ten male outfielders from the British Lacrosse squad (24.6 ± 2.3 years, 1.80 ± 0.08 m, 86.3 ± 4.5 kg) using force plates. The 90:90 isometric assessment was conducted before and after a single sixes lacrosse match to observe changes in hamstring force production. Bayesian paired sample's *t*-test and Hedge's *g* effect sizes were used to determine the level of evidence and magnitude of fatigue due to sixes lacrosse match play. **Results:** A strong level of evidence with moderate–large effect sizes for reduced peak force was observed (Bayes factor [BF] = 11.36–12.55; *g* = 1.18–1.20). Stronger levels of evidence and large magnitude reductions were observed for force at 100 and 200 ms (BF = 18.92–61.85; *g* = 1.55–1.63). **Conclusions:** Sixes lacrosse match play results in localized hamstring fatigue, which could explain the high frequency of hamstring strain injuries within elite men's sixes lacrosse players. The current sixes competition format includes multiple fixtures on a single day; therefore, practitioners need to prioritize recovery.

Keywords: peak force; rapid force; isometric; team sport; force plates



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1. Introduction

Hamstring strain injuries continue to be the most prevalent injury within team sports [1–3], with financial and competition success implications [4,5]. As with any injury, there are a range of risk factors, which can be categorized as external or internal and modifiable and non-modifiable [6–8], that have an association with injury incidence [9]. Internal non-modifiable risk factors are aspects such as age and previous injury [6,7,10], whereas external non-modifiable risk factors could be playing schedule and position [6,11–14]. Practitioners need to be acutely aware of the non-modifiable risk factors and their relationship with injury, as these factors likely have implications on the prescription of training. To address the influence of these internal and external non-modifiable risk factors, training should target modifiable risk factors to offset their influence [6,8]. The most frequently

assessed modifiable risk factor is hamstring strength [6,7,15], with eccentric strength showing the strongest evidence for reducing the risk of hamstring strain injury incidence [6,15]. However, the adoption of eccentric training within team sports such as soccer is frequently associated with low compliance and complaints from athletes and coaches [4,16,17], which likely results in eccentric assessment also being prohibitive during crucial periods such as competition or fixture congestion with expected muscle soreness [18]. Hence, alternative assessments are becoming commonplace within the field, with isometric assessments being preferential due to their low-fatigue nature, rapid assessment and the limited need for familiarization [19–22]. Moreover, they have been found to be both reliable and sensitive to fatigue [19–21,23,24], which is an important external non-modifiable risk factor [6,11–13].

With the increases in technology affordability and availability in sport, there has been an increase in the use of force plate technology [21], and assessing single-joint isometric strength is becoming common place [19,21,24]. Reductions in peak and rapid isometric force have been shown to occur for up to 72 h following fatiguing activity [19–21,23,24]. Within the literature, multiple positions have been considered for determining isometric hamstring force, including 90:90 (90° hip and knee flexion), 30:30 (30° hip and knee flexion), standing 90:20 (90° hip flexion and 90° knee flexion) and 60:75 (60° hip flexion and 70° knee flexion); all positions are reliable, with the three former positions being sensitive to fatigue [19–21,23–25]. As the hamstrings are required to rapidly resist the lengthening through the terminal swing phase of sprinting and produce large amounts of force rapidly on ground contact [26–29], the ability to produce rapid force is an essential attribute of the hamstrings. Isometric assessments using force plates are able to collect this data reliably [23,24,30]. Interestingly, it seems that rapid force is reduced for a longer period following a fatiguing activity such as match play [24]. These findings highlight the need to regularly and reliability monitor acute changes in both peak and rapid isometric hamstring strength within team sport athletes, especially in competition or periods of fixture congestion.

Sixes lacrosse is a small-sided lacrosse variant, with elements of playing structure taken from both field and box lacrosse, played across 32 min (4 × 8 min quarters), with the resultant physical demands being a series of repeated high-intensity efforts at high movement velocities [31,32]. Lower limb injuries have been identified as the most common within international sixes lacrosse athletes [33], with hamstring strain injuries frequently occurring through non-contact mechanisms [33]. Sixes lacrosse is due to make its inaugural appearance at the 2028 Olympics. As player welfare is paramount, practitioners should place player health as a top priority leading up to this event, as hamstring strain injuries are a leading non-modifiable risk factor for future injury [6], while niggles or non-time-loss injuries can lead to more severe injury incidence [34], with the latter frequently occurring within sixes [33]. Currently, players participate in multiple lacrosse disciplines (i.e., field, box and sixes) due to the similarities in playing styles and key sport-specific skills (e.g., offensive and defensive movements [i.e., accelerations, decelerations], shooting and passing). This increase in competitive demands results in increased chronic loading, which is an explanation for the high rate of non-time-loss injuries observed within sixes lacrosse players (e.g., tendinopathies) [33].

Recent investigations have identified that sixes lacrosse match play is fatiguing, with reductions in countermovement jump performance following international competition [35]. Interestingly, reductions in countermovement jump performance were minimal following a single match, with these reductions potentially being masked by reductions in body mass [35]. Therefore, localized assessments of single-joint force characteristics may be more sensitive to fatigue monitoring, which cannot be masked by alterations in body mass. Hence, the purpose to the present study was to identify if sixes lacrosse match

play in international male lacrosse players has a fatiguing effect leading to reductions in the peak and rapid force characteristics of the hamstrings. Due to sixes lacrosse squads comprising a maximum of 12 players, with typically two goal keepers, conventional null hypothesis testing may not be appropriate, with alternative approaches such as Bayesian providing viable alternatives [36]. Therefore, the aim of the present study was to observe the magnitude of the reductions in isometric hamstring force-generating capabilities [36,37]. A secondary exploratory aim was to observe if any relationships exist between match demands and changes in force–time characteristics. It was hypothesized that both peak and rapid measures of isometric force would be reduced as a result of playing sixes lacrosse. It was also hypothesized that changes in force–time characteristics would be related to match demands, including total distance and high-intensity actions (i.e., very-high-speed running, accelerations and decelerations).

2. Materials and Methods

An observational pre–post design was used to provide within-session reliability. Sample size estimation was not performed for Bayesian analysis, as this provides an indicator of the level of evidence based on the current sample size and projects how this might change with increased sample sizes, yet there remains a risk of type 2 error.

Ten male outfielders from the British lacrosse squad (24.6 ± 2.3 years, 1.80 ± 0.08 m, 86.3 ± 4.5 kg) participated in the present study, with a single match commencing at 16:00. Peak isometric force measurements were collected using force plates, before and after a single match play, to observe if sixes lacrosse match play resulted in hamstring fatigue. Between 41 and 33 min prior to commencing the standardized match warm up, all players performed the 90:90 isometric hamstring assessment. Following the match play, within 12–27 min of completing the match, all players repeated the assessment to determine changes because of fatigue. Dominant limb (DL) and non-dominant limb (NDL) were identified via the participants' preferred kicking limb. Participants were required to have had no hamstring-related injuries for ≥ 6 months prior to taking part. Organizational consent was acquired prior to approaching the participants, and all participants provided written informed consent, or parental/guardian assent where required, to participate in this study. Ethical approval was granted by the institutional ethics committee (HSR 0159; 19 March 2024) in accordance with the Declaration of Helsinki 2013. Participants completed the tests prior to their normal training day, following a standardized warm-up including squats, lunges, hamstring stretches, leg swings and calf raises. Prior to completing all testing, participants completed three practice trials at submaximal intensities.

The 90:90 isometric assessments were performed using a single force plate (Hawkin Dynamics (HD), Westbrook, ME, USA), with sampling at 1000 Hz, and data were collected using HD proprietary software (version 10.4.0). Force plates were zeroed between participants. Placed upon a wooden plyometric box at an appropriate height for each participant using a goniometer, the 90:90 isometric assessments were performed with participants lying in a supine position with their knee and hip at 90° flexion. Participants heel-rested on the force plate with footwear removed. The test was applied unilaterally, with the non-testing limb being placed fully extended next to the box and arms placed across the chest. Three trials for each limb were executed by the participants, driving their heel down into the force plate for 3–5 s. Following three submaximal trials, each trial was performed by the same practitioner who was an accredited strength and conditioning coach and sport scientist with experience in administering force plate assessments. All tests were performed in random order. Participants were instructed to remain as still as possible, without initiating a movement for at least a 1 s period to enable calculation of associated force–time data via HD proprietary software. Participants were instructed to *'pull their heel into the force*

plate as fast and as hard as possible', while the assessor secured the participants at the hips. Participants were required to repeat trials if their hips raised off the ground, which was determined by visual inspection or if a countermovement was performed, the latter of which was detected through inspection of the force trace following each repetition.

To collect locomotion data, global positioning system (GPS) microtechnology sampling at 10 Hz (Vector S7; Catapult Sports, Melbourne, Australia) was utilized. All players wore the GPS units within a fitted sports vest under all protective equipment (Catapult Sports, Melbourne, Australia), with a pocket positioned between the scapulae to hold a microsensor, which included a 10 Hz GPS chip and a 100 Hz triaxial accelerometer. The validity of GPS technology has been deemed acceptable for measuring movements associated with team sports competition [38–40]. All GPS microsensors were activated 10 min before match preparation to ensure clear satellite reception; all players were familiar with the equipment and protocols being conducted for data acquisition. Openfield software (version 3.7.0; Catapult Sports, Melbourne, Australia) was used to manually identify the start and end of each 8 min quarter from GPS data following acquisition, with the start and end of each quarter being time-matched. All data were filtered within the proprietary software (version 3.7.0). Thereafter, data from each match were exported into a Google sheets spreadsheet (Mountain View, CA, USA) to process the variables for analysis. Speed zone thresholds and minimum time used to identify efforts were determined as per original proprietary software.

Locomotion data were collected in Nottingham (United Kingdom). Data were exported and analyzed in Manchester (United Kingdom). The average and minimum number of satellites identified across the observation period were 17.7 ± 1.86 and 15, and the average horizontal dilution of precision across the observation period was 0.95 ± 0.11 [41].

Various activity variables were measured to comprehensively quantify the locomotive demands of international sixes lacrosse matches under World Lacrosse Sixes rules. Data were collected and are reported for the entire match irrespective of whether players were actively competing or substituted because of the dynamic nature of substitutions. Data were not collected during the 2 min inter-quarter breaks or 5 min half-time break during the match. Furthermore, no timeouts were used and no stoppages occurred during the monitored match. The GPS component of the microsensors was used to measure the absolute distance (m) and distances covered, performing various speed-mediated activities, including high-speed running (HSR) ($5.5\text{--}7.0\text{ m}\cdot\text{s}^{-1}$) and very-high-speed running (VHSR) ($>7.0\text{ m}\cdot\text{s}^{-1}$), with maximum velocity ($\text{m}\cdot\text{s}^{-1}$) also recorded. Triaxial accelerometers were used to detect the frequency (count) of accelerations ($>2\text{ m}\cdot\text{s}^{-2}$), decelerations ($>-2\text{ m}\cdot\text{s}^{-2}$). The various intensity and speed thresholds used required a 1 s minimum effort duration to record acceleration and deceleration counts, in line with the manufacturers' recommended default settings and previous research in field lacrosse [42].

Force–time data for each trial were automatically analyzed using HD proprietary software. Initially, force–time data were filtered to 50 Hz using a Butterworth filter. The HD proprietary software automatically identified the onset of force production using 3 standard deviations (SDs) of the stable weighing period, as supported by Guppy et al. [43]. Absolute peak force and forces at 100 and 200 ms were calculated for each trial, with the average of three trials being used for further analysis. The participants' dominant limb (DL) was identified as their kicking limb, with the opposite limb identified as the non-dominant limb (NDL) [44].

Statistical Analyses

Data are presented as mean $\pm$ SD. Normality was verified using the Shapiro–Wilk test ($W > 0.96$, $p > 0.05$). A priori alpha level was set at <0.05 . Absolute reliability was calculated using coefficient of variance (CV%) based off the sample SD and interpreted based on the upper bound 95% confidence interval (CI) as $<5.00\%$, 5.00 – 9.99% , 10.00 – 14.99% and $>15\%$ as excellent, good, moderate, and poor, respectively. Relative reliability was assessed using two-way absolute agreement (3,1) ICC [45], ICC values were interpreted based on the lower bound 95% CI (ICC; poor <0.49 , moderate 0.50 – 0.74 , good 0.75 – 0.89 and excellent >0.90) as suggested by Koo & Li [45].

Isometric peak and rapid forces for each limb attained were extracted for further analysis, providing the mean and standard deviation (SD). Bayesian paired sample's t -test was used to determine the level of evidence, indicating the effect of fatigue on match play on the DL and NDL, independently. Bayesian Pearson correlations (r) were also determined to determine the level of evidence supporting any relationships between the match demands and changes in force–time characteristics. The Bayes factor (BF_{10}), where evidence is established for the alternative hypothesis (H_1) over the null hypothesis (H_0), was interpreted as 1–3, anecdotal; 3–10, moderate; 10–30, strong level of evidence to support the hypothesis, whereas 1.00–0.33, weak; 0.33–0.10, moderate; and 0.09–0.03, strong evidence supported the null hypothesis [37]. The BF_{10} prior was set as the default to 0.707 [37]. Hedge's g effect sizes and 95% CIs were also calculated to determine the magnitude of the difference. The effect size was interpreted as <0.20 , trivial; 0.20 – 0.59 , small; 0.60 – 1.19 , moderate; ≥ 1.20 , large. Pearson's r correlations were interpreted as <0.10 , 0.10 – 0.29 , 0.30 – 0.49 , 0.50 – 0.69 , 0.70 – 0.89 and ≥ 0.90 as trivial, small, moderate, large, very large and nearly perfect, respectively [46].

3. Results

3.1. Reliability

Absolute within-session reliability pre-match was found to be good–moderate (Table 1), with good–excellent relative reliability.

Table 1. Within-session absolute and relative reliability for peak and rapid force in 90:90 isometric hamstring assessment.

	CV% (95% CI)	ICC (95% CI)
Peak force	4.45 (2.50–6.40)	0.920 (0.852–0.961)
Force at 100 ms	7.71 (4.33–11.08)	0.963 (0.930–0.982)
Force at 200 ms	6.69 (3.76–9.62)	0.972 (0.947–0.987)

CV% = coefficient of variation percentage, ICC = intraclass correlation coefficient, CI = confidence interval.

3.2. Pre- to Post-Match Changes

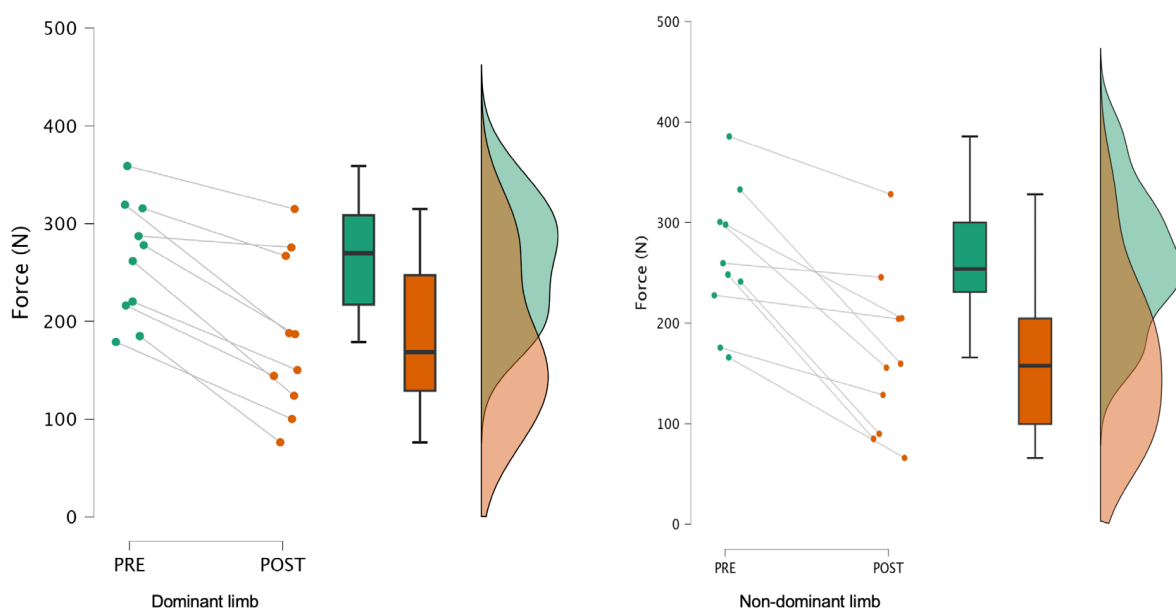
The mean $\pm$ SD for pre- to post-match changes in the 90:90 isometric hamstring assessment for peak force, force at 100 ms and 200 ms are presented in Table 2. The BF and Hedge's g effect sizes are also presented in Table 2.

Individual pre- to post-match individual changes in the 90:90 isometric hamstring force-generating capabilities for the DL and NDL peak force are presented in Figure 1.

Table 2. Descriptive and statistical pre- to post-match changes in peak and rapid isometric force in 90:90 assessment.

Measure	Pre Mean $\pm$ SD	Post Mean $\pm$ SD	BF ₁₀	Hedge's g (95% CI)	BF Interpretation	Effect Size Interpretation
NDL Peak Force (N)	398.62 $\pm$ 86.63	369.97 $\pm$ 86.39	11.36	1.18 (0.34–1.98)	Strong	Moderate
NDL Force at 100 ms (N)	207.59 $\pm$ 67.87	118.07 $\pm$ 38.04	59.63	1.61 (0.64–2.56)	Strong	Large
NDL Force at 200 ms (N)	259.79 $\pm$ 70.94	162.60 $\pm$ 85.10	61.85	1.63 (0.64–2.57)	Strong	Large
DL Peak Force (N)	450.13 $\pm$ 66.31	405.36 $\pm$ 76.85	12.55	1.20 (0.36–2.01)	Strong	Large
DL Force at 100 ms (N)	193.08 $\pm$ 73.25	121.94 $\pm$ 66.38	18.92	1.55 (0.62–2.48)	Strong	Large
DL Force at 200 ms (N)	271.07 $\pm$ 82.11	170.54 $\pm$ 90.42	22.60	1.60 (0.60–2.51)	Strong	Large

SD = standard deviation, BF = Bayes factor, CI = confidence interval, NDL = non-dominant limb, DL = dominant limb.

**Figure 1.** Pre- to post-match changes in peak isometric force. Green = pre-match values and distribution; Orange = post-match values and distribution.

3.3. Match Demands and Relationship to Pre- to Post-Match Changes

The locomotion demands for the sixes lacrosse match are presented in Table 3.

Table 3. Descriptive statistics for sixes lacrosse match.

	Total Distance (m)	High-Speed Running (m)	Very-High-Speed Running (m)	Max Velocity (m·s ⁻¹)	Accelerations (#)	Decelerations (#)
Mean $\pm$ SD	2551.89 $\pm$ 256.48	1236.38 $\pm$ 364.23	270.41 $\pm$ 85.58	8.94 $\pm$ 0.33	31.20 $\pm$ 6.53	37.10 $\pm$ 8.57

SD = standard deviation.

The results of the exploratory analysis using Bayesian Pearson's correlations (r) and BF₁₀ are presented in Table 4, as the differences between pre- and post-match for DL and

NDL were comparable. Data were pooled for pre–post changes as the workload was system-dependent (i.e., cannot differentiate between DL and NDL independently from the external load) and the exploratory nature of this analysis. In agreement with the hypothesis, a strong relationship with a strong level of evidence was observed between changes in peak force and total distance, explaining 29% of the variance ($R^2 = 0.288$). Interestingly, a moderate relationship with a strong level of evidence was also observed between the change in peak force and high-speed distance, explaining 25% of the variance ($R^2 = 0.247$). High-intensity measures (i.e., maximal velocity, very-high-speed running and decelerations) showed strong relationships with the change in force at 200 ms, with a strong level of evidence, explaining 36%, 26% and 27% of the shared variance ($R^2 = 0.366$, 0.258 and 0.275, respectively) for maximal velocity, very-high-speed running and decelerations, respectively. All other relationships were trivial–moderate in magnitude, with anecdotal–moderate levels of evidence supporting the hypotheses.

Table 4. Bayesian Pearson’s correlations with 95% credible intervals and Bayes factors.

	Total Distance		Max Velocity		High-Speed Running		Very High-Speed Running		Accelerations		Decelerations	
	<i>r</i> (95% CrI)	BF ₁₀	<i>r</i> (95% CrI)	BF ₁₀	<i>r</i> (95% CrI)	BF ₁₀	<i>r</i> (95% CrI)	BF ₁₀	<i>r</i> (95% CrI)	BF ₁₀	<i>r</i> (95% CrI)	BF ₁₀
Peak force	0.537 (0.231 to 0.728)	11.87	0.333 (0.108 to 0.551)	4.55	0.497 (0.235 to 0.737)	10.34	0.236 (0.054 to 0.411)	1.65	0.199 (−0.054 to 0.411)	1.51	0.218 (0.054 to 0.378)	2.98
Force at 100 ms	0.118 (−0.281 to 0.420)	0.88	0.502 (0.212 to 0.698)	9.78	0.201 (0.008 to 0.403)	1.33	0.386 (0.154 to 0.607)	4.58	0.231 (0.044 to 0.385)	2.09	0.402 (0.229 to 0.578)	9.16
Force at 200 ms	0.334 (0.068 to 0.605)	4.78	0.605 (0.372 to 0.748)	12.32	0.315 (0.121 to 0.535)	4.06	0.508 (0.245 to 0.757)	10.57	0.300 (0.123 to 0.477)	3.56	0.524 (0.245 to 0.757)	11.52

Note: 95% CrI = 95% credible interval; BF₁₀ = Bayes factor.

4. Discussion

The purpose of the present study was to observe the magnitude of the reductions in the isometric hamstring force-generating capabilities during sixes lacrosse match play in international male lacrosse players, which could elevate the risk of hamstring strain injury. In agreement with the first hypothesis, there were moderate–strong levels of evidence supporting the reductions in both peak and rapid isometric force production following a sixes lacrosse match, with a moderate–large magnitude. For the DL, the reductions were consistent between peak force and rapid force measures; contrastingly, the magnitude of reduction in the rapid force in the NDL was far greater (i.e., force at 100 ms and 200 ms) in comparison to that in the peak force. Furthermore, there was a strong level of evidence supporting the hypothesis of the observed relationships between match characteristics and the change in force–time characteristics. These relationships highlight that the reductions in either peak force or rapid force are related to the demands the sixes players are exposed to, with high volumes (i.e., total distance and high-speed running distance) having strong–moderate relationships with the reductions in peak force and high-intensity actions (i.e., maximal velocity, very-high-speed running distance and decelerations), having strong relationships with the reduction in force at 200 ms. The observed reductions in both peak

and rapid force could partially explain the high rate of hamstring injury incidence observed within men's sixes lacrosse players [33].

The magnitude of the changes in peak force and rapid force differed between limbs: the DL showed consistent reductions in both peak and rapid force. This could be explained by the meaningful relationships observed between the peak and rapid force measures in isometric assessments, including within the 90:90 isometric hamstring assessment [30]. Hence, the reductions in peak force could explain the near-identical reductions in rapid force [47,48]. However, the magnitude of the reductions in rapid force was greater than that observed for peak force for the NDL, indicating that there were further confounding factors influencing the reduction in rapid force in the NDL other than the reduction in peak force [47]. The variation in the reduction in force–time characteristics could be related to the match demands the players are exposed to, with volume and intensity metrics showing varying relationships with the magnitude of the change. Rapid force was meaningfully related to metrics involving high-velocity actions either during high-velocity running (i.e., sprinting $> 7 \text{ m}\cdot\text{s}^{-1}$) or high-intensity deceleration actions, which may be damaging actions due to the eccentric loading [49], although further investigation is required to determine if muscle damage is the cause of the reductions in force. Contrastingly, peak force was meaningfully related to total distance and high-speed running, which was likely due to the total distance of high-speed running. These relationships indicate that the decreases in force–time characteristics were dependent on the match demands players were exposed to and should be considered within training and recovery. Matinlauri et al. [20] noted that the 90:90 isometric hamstring assessment may be less sensitive to fatigue following a fatiguing-simulated protocol in contrast to a 90:20 position, especially when noting changes greater than 24 h post-protocol. The findings of the present study demonstrate that the 90:90 isometric hamstring may possess adequate sensitivity to fatigue, with moderate–large decreases identified, in contrast to the small–moderate decreases in peak force identified by Matinlauri et al. [20]. However, to the best of the authors' knowledge, no study has yet reported the changes in both peak and rapid force from = competitive team sport match play, supporting the novelty of the present study. Cosio et al. [24] observed similar and longer-lasting reductions in the early rate of torque development in the 90:20 isometric hamstring assessment following a competitive soccer match, suggesting that these reductions are related to a loss of Ca^{2+} homeostasis and a reduced stiffness of cellular force transmission [24]. Although why the NDL was affected to a greater extent than the DL requires further investigation, one suggestion is the identification of limb dominance or the specific demands of sixes lacrosse, resulting in muscle damage.

The small sample size in the present study, due to the associated squad size, could increase the risk of type 2 error; thus, a Bayesian analysis was applied to determine the level of evidence of the differences observed pre- to post-match [36]. Despite the moderate–strong levels of evidence to moderate–large magnitudes, considerable inter-individual differences were observed (Figure 1). Barber et al. [48] suggested using a quadrant-based system to interpret the peak and rapid force data within isometric hamstring assessments, grouping participants into “*weak and slow*”, “*strong and slow*”, “*weak and fast*” and “*strong and fast*”. This would enable practitioners to identify if and where people are more affected, which could indicate the mechanism of fatigue. McCall et al. [21] suggested that the reductions observed in isometric peak force within the hamstrings are related to muscle damage. Previous work on fatigue has suggested that reductions in peak force are associated with reductions in muscle activation, assessed via electromyography (EMG) [50,51]. Decreases in EMG amplitude normalized to M-wave amplitude during a maximal task have been suggested to be attributed to central fatigue, with central fatigue reflected in suboptimal neural drive [50,51]. Reductions in early force production (i.e., rate of force development)

may be associated with the central fatigue or sub-optimal neural drive [47,50], as suggested by the similar decreases in peak force and rapid force in the present study [47,48], in contrast to the evidence of peripheral fatigue (i.e., localized muscle damage) affecting Ca^{2+} homeostasis and cellular force transmission or sarcolemma excitability, as suggested previously, although this requires further investigation with appropriate methodologies [50,51]. The peripheral fatigue and associated reductions in early force production have been evidenced in post-soccer-match play by increases in both creatine kinase and the ratio of creatine kinase to aminotransferase [24]. Increases in creatine kinase ranging from 32 to 60% have been observed following sprint-based exercises [52], which could occur following sixes lacrosse match play as a result of the high-intensity nature of sixes lacrosse, with repeated acceleration and deceleration [31,32]. However, further work is required to determine if the same markers of muscle damage are observed following a sixes lacrosse match, which may further explain the reductions in force-generating characteristics.

Non-contact hamstring strain injuries frequently occur within sixes lacrosse [33], consistent with other competitive team sports [1–3]. The most common mechanisms are related to sprinting mechanisms [53,54], which have the potential for the hamstring strain injuries to occur within either the late-swing or early-stance phase [53,55]. Bramah et al. [56] highlighted that hamstring strain injury is the result of an applied strain, as experienced during sprinting, overcoming the strain capacity of the hamstrings. The strain capacity of a muscle is related to the associated risk factors [7], with hamstring strength being a modifiable risk factor for injury [6,15]. The hamstrings are required to produce high forces to overcome the momentum of the shank during the terminal swing phase [26,28,29], with the hamstrings producing up to $8.95 \pm 1.66 \times$ of the body weight during the swing phase of the sprint cycle during sprint running ($\sim 9 \text{ m}\cdot\text{s}^{-1}$) [57]. Currently, the role of rapid-force-generating capabilities in hamstring strain injury risk has not been investigated in the literature, despite the importance of peak forces [6,15]. The requirement produce force rapidly is clear, with ground contact times of approximately $0.12 \pm 0.01 \text{ s}$ during sprint running [57] and swing times of $0.35 \pm 0.01 \text{ s}$ [58]. The results of the present study suggest that the fatigue-induced reductions in peak and rapid force contributed to the rate of hamstring strain injuries within sixes lacrosse; however, the actual mechanism of hamstring strain injury incidence within sixes lacrosse needs further study as it is currently unknown.

The present study is not without its limitations. Firstly, as sixes match day squads are constrained to a maximum of 12 players, typically comprising two goalkeepers, this limited the sample size available for single-match observation. This elevated the risk of type 2 errors, and therefore these findings should be interpreted with caution. Future work should observe multiple matches to enhance the available sample size and use global positioning system technology to determine if the changes in single-joint force-generating capabilities are related to match demands. Recent work has established that a single match may not induce fatigue, with only changes in body mass reflecting alterations in countermovement jump performance [35]. However, changes in kinetic measures have been observed following three matches in a single day or a full tournament [35]. Only the 90:90 isometric hamstring assessment was used in the present study; however, other positions may better reflect hamstring muscle tendon unit lengths experienced within sprinting (e.g., 90:20 or 30:30), requiring further investigation [19]. However, the present study is the first to report changes in the rapid force characteristics in the 90:90 assessment following fatiguing activity, with only peak forces observed previously [20,21]. Finally, the results presented within the present study were only obtained from male international sixes players, and further investigation is required for female lacrosse players, especially

given the high incidence of anterior cruciate ligament injuries within female lacrosse players [59,60].

5. Conclusions

The primary finding of the present study is that there were moderate–strong levels of evidence supporting reductions in both peak and rapid isometric force production following a sixes lacrosse match, to a moderate–large magnitude. A strong level of evidence supported the hypothesis of the observed relationships between match characteristics and the change in force–time characteristics, specifically with the repeated high-intensity nature of sixes lacrosse match play. Practitioners need to be aware of acute fatigue following match play, with regards to making decisions on the implementation of recovery strategies and the potential risk for hamstring strain injuries, which are highly prevalent in male international sixes lacrosse players [33]. Moreover, the demands of sixes appear to be related to the observed reductions in force–time characteristics, highlighting that the physical preparation of sixes athletes should be carefully designed. The current sixes competition format requires teams to compete frequently within a condensed period (e.g., a three- to five-day window), with multiple events on a single day (e.g., two to three matches per day). Therefore, recovery needs to focus on maximizing immediate recovery through fundamental recovery protocols, including sleep, nutrition and rehydration, as well as the potential to incorporate other external aids such as the use of cooling and heating strategies [61] and blood flow restriction [62] to aid post-match recovery. In preparation for these periods of match congestion, practitioners should look to expose sixes athletes to these demands via replicating the demands over short periods to offer a protective effect. Similarly, improving maximal strength, specifically eccentric strength, would aid in damage protection via the repeated bout effect [63].

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Abbreviations

The following abbreviations are used in this manuscript:

BF	Bayes factor
DL	Dominant limb
NDL	Non-dominant limb
HSR	High-speed running
VHSR	Very-high-speed running
HD	Hawkin dynamics
CV%	Coefficient of variation percentage

ICC	Intra-class correlation coefficient
CI	Confidence interval
SD	Standard deviation

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