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RESEARCH ARTICLE

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Rapid force generation during unilateral isometric hamstring assessment: reliability and relationship to maximal force

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ABSTRACT

Limited research has reported the reliability of rapid force generation characteristics during isometric assessments of the hamstrings. Therefore, the purpose of the present study was to determine the between-session reliability of rapid force generating characteristics of the hamstrings and relationship to maximal force production. Twenty-three female soccer players (age: 20.7 ± 4.7 years; height: 168.7 ± 5.9 cm; body mass: 64.4 ± 6.7 kg) performed three unilateral trials of the 90–90 isometric hamstring assessment, on two separate occasions, separated by 7 days. Peak force, force at 100- and 200 ms and average rate of force development (aRFD) over 100- and 200 ms epochs were calculated. Absolute and fair-good reliability was observed for peak force and all rapid force generating measures (<8.33CV%, ICC >0.610). Significant and meaningful relationships ($p < 0.001$, $r > 0.802$) were observed for all rapid force generating measures and peak force. The 90–90 isometric assessment can be used to assess peak and rapid force generating reliably to enable practitioners to confidently track changes in performance over time as part of fatigue monitoring and management.

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KEYWORDS
Female soccer; hamstring strength; force plates; fatigue monitoring

Introduction

Hamstring strain injuries (HSIs) remain one of the most prevalent non-contact muscular strain injuries occurring within team sports (Brooks et al., 2006; D'Alonzo et al., 2021; Ekstrand et al., 2011, 2016; Malone et al., 2018; Panagodage Perera et al., 2019; Read et al., 2018; Roe et al., 2018). Soccer has one of the highest rates of HSI occurrence, which is partly due to two of the primary proposed mechanisms of HSIs frequently occurring during match play and training, i.e., kicking or high-speed running (Danielsson et al., 2020; Opar et al., 2012). During high-speed running, for the hamstrings to resist the rapid knee extension during the terminal swing phase (Chumanov et al., 2011), they are required to produce up to 10.5 N/kg in resisted lengthening forces (Nagano et al., 2015). Heiderscheit et al. (2005) approximated that a HSI event occurred at some point during the late swing phase or the very initial stance phases with the earliest indication of an injury occurring only 0.1 s following foot contact (Heiderscheit et al., 2005; Schache

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et al., 2009). Within professional soccer, sprinting-based injuries occur most frequently during sprinting activities, specifically within the bicep femoris long head (BF_{LH}) (Ekstrand et al., 2023). This observation highlights that the ability for the hamstrings to produce extremely high forces rapidly is essential.

A secondary cause of high rates of HSI incidence in soccer is generally a lack of compliance to a known HSI prevention exercise (i.e., Nordic hamstring exercise (NHE)) (Bahr et al., 2015; Ekstrand et al., 2022, 2023), which has been shown to have a profound effect on the successfulness of HSI prevention (Ripley et al., 2021). The implementation of the NHE has been shown to increase proposed modifiable risk factors of HSI (Opar et al., 2012), including BF_{LH} fascicle length and eccentric hamstring strength (Cuthbert et al., 2019). As a modifiable risk factor for HSI eccentric hamstring strength was identified as a measure of injury risk, with the Nordbord being used to identify risk (Bourne et al., 2015; Opar et al., 2015, 2013; Timmins et al., 2016). However, more recently, it has been established that with team sports, pre-season eccentric hamstring strength testing provided minimal insight into HSI incidence (Opar et al., 2021). Within the systematic review by Opar et al. (2021), it was highlighted that more frequent follow-up assessments could present different findings as the studies included within the systematic review and meta-analysis follow-up period was between 3 and 10 months.

As regular monitoring of hamstring strength could provide greater insight into potential HSI risk, the ability to determine fatigue and decrements in performance will help practitioners identify high-risk occasions and adapt training to avoid potential injury sustainment (e.g., removal or limiting of high-speed running) (Opar et al., 2012). Following competitive and simulated match play or repeated sprinting, eccentric hamstring strength has been shown to be reduced (Greig, 2008; Matthews et al., 2017; Timmins et al., 2014); however, as previously identified, the NHE is poorly adopted in team sports, hence other methods of monitoring hamstring strength are required. Isometric hamstring strength assessments have been used to identify changes in strength due to fatigue and HSI injury risk (Bettariga et al., 2023; Constantine et al., 2019; Matinlauri et al., 2019; McCall et al., 2015; Wollin et al., 2016, 2017, 2018), with a variety of technologies, including externally fixed dynamometers and force plates. With increasing availability of force plate technology, which can collect data and provide instant feedback, force-plate-based isometric hamstring assessments are becoming increasingly common, with several iterations but the most common being 90° of hip and knee flexion (90–90°) (Bettariga et al., 2023; Constantine et al., 2019; Cuthbert et al., 2021; Matinlauri et al., 2019; McCall et al., 2015). Despite the low association between isometric hamstring assessments using force plates and eccentric hamstring strength measures (Moreno-Perez et al., 2020), the isometric assessments have been identified as sensitive enough to monitor fatigue, with previously identified reliability and measurement error scores (4.34–11.0% coefficient of variation, 0.698–0.95 (0.274–0.980), intraclass correlation coefficient (ICC) (95% confidence intervals (CI) and 26.2–31.9 N minimal detectable difference) (Bettariga et al., 2023; Constantine et al., 2019; Cuthbert et al., 2021; Matinlauri et al., 2019; McCall et al., 2015). However, only a single study to date has included rapid force generation (e.g., rate of force development (RFD)) (Bettariga et al., 2023), in male semi-professional soccer players. Therefore, the purpose of the present study was to determine the between-session reliability of rapid force generating characteristics and identify any relationship between rapid and maximal force production, in professional female soccer players. It was hypothesised that all measures would be reliable with meaningful relationships between peak force and rapid force production.

Materials and methods

Participants

Twenty-three female soccer players playing in the Women's Super League, all of whom had a minimum of 2 years of resistance training experience (age: 20.7 ± 4.7 years; height: 168.7 ± 5.9 cm; body mass: 64.4 ± 6.7 kg) volunteered to participate in the study. Participants were required to have had no hamstring-related injuries for ≥6 months prior to taking part. Organisational consent was acquired prior to approaching the participants and all participants provided written informed consent, or parental/guardian assent where required, to participate in the study. Ethical approval was granted by the institutional ethics committee in accordance with the declaration of Helsinki. α-priori sample size estimation suggested a minimum sample of 20 participants to achieve a minimum acceptable power of 80%, with no systematic differences between repeated measures to achieve a target width of 0.35 based on two repeated measures (Mokkink et al., 2022).

Experimental design

A repeated measures cross-sectional design was used to determine the reliability of isometric hamstring strength assessment. Participants completed the tests prior to their normal training day on two occasions 72 h apart. The familiarisation session was carried out 48 h after a competitive fixture, following their recovery day, with the testing session completed 3 days after familiarisation, allowing at least 48 h recovery prior to their next competitive fixture.

90–90 isometric hamstring

The 90–90 isometric assessments were measured using a force plate (Kistler Type 9286AA: Kistler Instruments Inc, Amherst, NY, USA), sampling at 1000 Hz and collected using Kistler's BioWare software. Placed upon a wooden plyometric box at an appropriate height for each participant using a goniometer, this was determined by participants lying in a supine position with their knee at 90° of flexion, their heel resting on the box and their hip at an angle appropriate to allow the lower shank to be parallel to the floor (i.e., 90°) (Figure 1). The test was applied unilaterally with the non-testing leg being placed fully extended next to the box and arms placed across the chest. Three trials for each leg were executed by the participants driving their heel down into the force platform for 3–5 s following three submaximal trials, similar to the previous isometric tests such as the isometric mid-thigh pull. Participants were instructed to remain as still as possible, without initiating a movement for at least a 1-s period before the instructions to pull to permit the calculation of limb weight

Figure 1. Representation of the 90–90 isometric assessment.

and associated force-time data including onset. 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.

Data analysis

Raw force-time data for each trial were analysed using a customised Microsoft Excel spreadsheet (version 2019, Microsoft Corp., Redmond, WA, USA). Peak force, force at 100- and 200 ms and average RFD (aRFD) from onset over a 100- and 200 ms epoch were calculated from the net force values (excluding limb weight established from the 1-s initial weighing period) for each trial. Onset of force was identified as five standard deviations (SD) from the 1 s quiet period (Dos'Santos et al., 2017). The mean of the three trials was taken and used for further analysis.

Statistical analyses

All statistical analyses were conducted using SPSS for Windows version 26 (IBM SPSS Inc, Chicago, IL). Data are presented as the mean ± SD. Normality was verified using the Shapiro-Wilk's test. An a priori alpha level was set at <0.05. Absolute reliability was calculated using coefficient of variance (CV%) based off the sample SD and 95% CI, interpreted 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) intraclass correlation coefficients (ICC) (Koo & Li, 2016; Kottner et al., 2011; McGraw & Wong, 1996; Shrout & Fleiss, 1979), ICC values were interpreted based on the lower bound CI (ICC; poor <0.49, moderate 0.50–0.74, good 0.75–0.89 and excellent >0.90) as suggested by Koo and Li (2016).

The standard error of measurement (SEM) and smallest detectable difference (SDD) for each variable were calculated to establish measurement error scores. The SEM was calculated using the following formula, where SD_{pooled} represents the pooled SD across the two testing sessions:

$$SD_{Pooled} \times \sqrt{1 - ICC}$$

The SDD was calculated using the following formula:

$$\left(1.96 \times \sqrt{2}\right) \times SEM$$

Differences between testing sessions were evaluated using a series of t-tests, with Bonferroni post hoc analysis. The magnitude of differences was also calculated using Cohen's *d* effect sizes and interpreted based on the recommendations of Hopkins (2006) (0.00–0.19 = trivial, 0.20-- 0.59 = small, >0.60 = moderate).

Pearson's correlation coefficients (*r*) with 95% CI, coefficient of determination (R^2) and percentage of explained variance were calculated to determine if any relationships exist between peak force and rapid force generating measures. Relationships between measures were interpreted using Hopkins (2006) scale, 0–0.1, 0.11–0.30, 0.31–0.50, 0.51–0.70, 0.71–0.9 and >0.90, as trivial, small, moderate, large, very large and nearly perfect, respectively. All Pearson's correlation coefficients (*r*) were corrected for familywise using Bonferroni correction.

Results

Good-excellent absolute and poor-moderate relative reliabilities were observed for all rapid force generating measures (<8.33CV%, ICC >0.610), with excellent absolute and good relative reliability observed for peak force (2.84CV%, ICC = 0.898) (Table 1).

Significant and meaningful relationships ($p < 0.001$, $r > 0.802$) were observed between all force-generating measures, with stronger associations observed at 200 ms (Figures 2 and 3).

Table 1. Between session mean, standard deviation (SD), absolute and relative reliability and absolute and relative (%) measurement error scores.

	Mean (SD)			Between session measures			
	Session 1	Session 2	Cohen's *d* effect size (95% CI)	CV% (95% CI)	ICC (95% CI)	SEM (%)	SDD (%)
Peak force (N)	215.15 (44.16)	206.68 (46.66)	0.19 (−0.63;1.01)	2.84 (2.02;3.66)	0.898 (0.827;0.944)	1.91 (0.91)	5.29 (2.51)
Force at 100 ms (N)	123.48 (34.52)	115.75 (39.38)	0.21 (−0.61;1.03)	4.57 (3.25;5.89)	0.784 (0.617;0.915)	3.07 (2.57)	8.51 (7.11)
Force at 200 ms (N)	153.44 (39.22)	137.30 (42.59)	0.39 (−0.44;1.21)	7.38 (5.25;9.61)	0.770 (0.611;0.892)	6.25 (4.30)	17.32 (11.92)
aRFD over 100 ms (N/S)	1234.84 (345.17)	1097.50 (393.84)	0.37 (−0.46;1.19)	8.33 (5.92;10.74)	0.642 (0.463;0.787)	58.11 (4.98)	161.07 (13.81)
aRFD over 200 ms (N/S)	767.20 (196.12)	816.50 (212.95)	0.24 (−0.58;1.06)	4.40 (3.13;5.67)	0.610 (0.451;0.732)	18.77 (2.37)	52.03 (6.57)

SD = standard deviation, CV% = coefficient of variation percentage, ICC = intraclass correlation coefficient, SEM = standard effort of the measurement, SDD = smallest detectable difference, aRFD = average rate of force development.

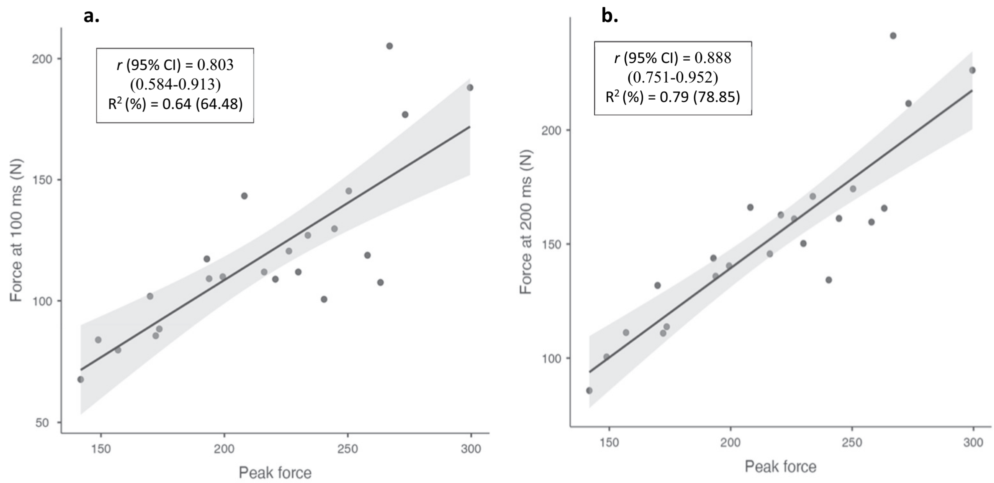

Figure 2. (a,b) Scatterplots with linear trend line and 95% CI, Pearson's correlation coefficient (*r*) with 95% CI and coefficient of determination (R^2) with percentage of explained variance illustrating the relationship between peak force and (a) force at 100 ms, (b) force at 200 ms.

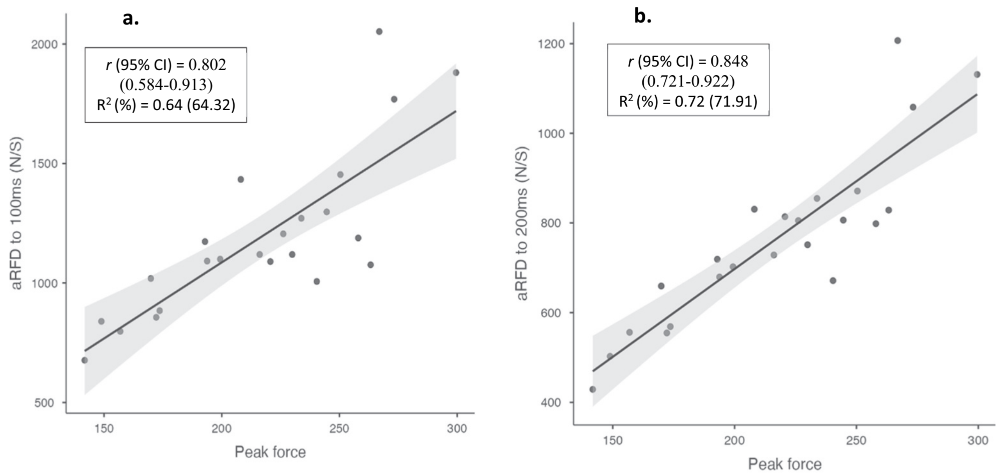

Figure 3. (a,b) Scatterplots with linear trend line and 95% CI, Pearson's correlation coefficient (*r*) with 95% CI and coefficient of determination (R^2) with percentage of explained variance illustrating the relationship between peak force and (a) aRFD over 100 ms and (b) aRFD over 200 ms.

Rapid force generating measures were able to explain >64% of peak force attained in the isometric hamstring assessment (Figures 2 and 3). Force at 200 ms and aRFD over 200 ms was able to explain a greater percentage of variance in peak force, than both measures taken over 100 ms.

Discussion and implications

The aims of the present study were to determine the reliability of peak force and rapid force generating measures during a unilateral isometric hamstring assessment within female soccer players and explore the relationships between peak force and rapid force generating measures (force at 100 and 200 ms and aRFD over 100 and 200 ms). The results from this study revealed that peak force and rapid force generating measures (specifically force at 100 ms and 200 ms) were reliable and could be longitudinally tracked, with only trivial to small differences between sessions. Excellent absolute reliability and good relative reliability identified for peak force, and good-excellent absolute reliability and poor-moderate relative reliability identified for all rapid force generating measures, with poor relative reliability observed for aRFD over 100 and 200 ms. Statistically significant and very large relationships were identified between all measures, in agreement with our hypothesis that stronger associations were seen at 200 ms in comparison to 100 ms for force at set time points and aRFD.

The findings of the present study are consistent with previous literature (Bettariga et al., 2023; Constantine et al., 2019; Cuthbert et al., 2021; Matinlauri et al., 2019; McCall et al., 2015), with good-excellent levels of reliability for peak force which could be used to track changes over time either acutely with changes through fatigue, or chronically with changes due to training. Within the present study, rapid force generating measures were found to be good-excellent absolute reliability, albeit with only fair relative reliability; this is consistent with the results of Bettariga et al. (2023) with moderate relative reliability also observed. Contrastingly, there was poor absolute reliability identified in RFD between 50–100 ms and 100–150 ms (Bettariga et al., 2023). It is crucial for variables to be determined as reliable and remain so over time, especially for repeated measures which could highlight injury risk and potentially be used for training adjustment as these could be impactful on an athlete or teams' success or athletic potential. To achieve reliable measures, the methods need to be consistently applied; this includes set up, instructions, data collection and data analysis, which may require standard operating procedures designed and followed within a multi-disciplinary team.

The reliability observed within the present study for a single joint isometric assessment using force plates is similar to what has been observed previously for multi-joint assessment of isometric strength, with peak force having good-excellent test-retest reliability (Grgic et al., 2022). Similar to the present study, rapid force generating characteristics (force at set time points and RFD) within the isometric mid-thigh pull have displayed lower levels of reliability than peak force (Dos'Santos et al., 2017; Guppy et al., 2022), with measures of RFD possessing lower reliability than force set time points (Dos'Santos et al., 2017; Guppy et al., 2022). This similarity does present an interesting point which could be applicable for isometric hamstring test used within the present study. If measures of RFD are less reliable than force at set time points, it is prudent for practitioners to be aware of this as this would impact on its usability for fatigue monitoring, as large fluctuations in RFD could be expected due to biological error. However, if force at 100 or 200 ms increases, RFD will have also increased but any change will less likely be down to biological error. However, the sensitivity of all the rapid force generating measures to fatigue requires further observation, as this will help determine their usefulness to practitioners.

The present study also highlights that very large associations between peak force and rapid force generating capacity were stronger at 200 ms in comparison to 100 ms for force at set time points and aRFD; this is consistent with previous single joint literature observing stronger explained variance with increases from the time of onset in knee-extension-based assessments (Andersen & Aagaard, 2006; Folland et al., 2014). This finding is also consistent with multi-joint assessments, such as the isometric mid-thigh pull, whereby rapid force generating measures are at longer time periods (Comfort et al., 2019). The authors also suggested that expressing early force production as a percentage of peak force could provide greater insight into training adaptations and warrants further investigation (Comfort et al., 2019).

The present study is not without its limitations; first, as discussed, testing methods or standard operating procedures should be carefully considered as one potential source of error could be from wearing shoes, where the rubber sole may dampen a force response. Similarly, measures may not be truly maximal if athletes are not secured to the ground, if trials are failed when hips raise or if there is an accurate representation of isometric hamstring force (or strength). Therefore, further research is required to explore these methodological aspects that could change the observed results. Moreover, similar to the research in the isometric mid-thigh pull (Dos'Santos et al., 2016, 2017), the methods used to analyse data collected can impact the findings. Researchers should look to explore the effect of sampling frequency and onset thresholds for isometric hamstring assessments including the 90–90 isometric assessment. If a reliable and accurate onset threshold can be identified other than 5 × SD as used within the present study, this could be imbedded within commercially automatic software which is now frequently used by practitioners to provide rapid feedback.

Peak and rapid force generating measures can be collected using the 90–90 isometric assessment within female soccer players reliably. The 90–90 isometric assessment could be used by practitioners to effectively track changes in performance as part of a holistic performance programme and identify positive adaptations as a result of training. It could also be used to monitor and inform practitioners of acute player fatigue; this could indicate the need for intervention strategies and/or training manipulation. Training manipulation could come in the form of complete or partial removal from training to minimise the risk of HSI (Malone et al., 2018). However, a need for standardised methods for practitioners and further investigation on the sensitivity of these measures to fatigue are required.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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