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ORIGINAL ARTICLE

Effect of Sampling Frequency on a Unilateral Isometric Hamstring Strength Assessment Using Force Plates

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Abstract

The purpose of this study was to determine the effect of sampling frequency on the 90–90° (90-degrees hip and knee flexion) isometric hamstring assessment. Thirty-three elite female soccer players (age: 18.7 ± 3.7 years; height: 158.3 ± 5.9 cm; body mass: 62.8 ± 5.5 kg) performed three unilateral trials on a single occasion of the 90–90° isometric hamstring assessment. Force-time data were collected using force plates at 1000 Hz and down sampled to 500-, 250-, and 100 Hz. Peak force (N), force (N) at 100- and 200 ms and average rate of force development (aRFD) (N/s) over a 100- and 200 ms epoch were calculated. A repeated measures of analysis of variance and effect size was used to compare means. Excellent absolute and good relative reliability was observed for peak force across all sampling frequencies. Force at 100- and 200 ms and aRFD over 100 ms and 200 ms resulted poor-moderate relative reliability and poor-excellent absolute reliability. No significant trivial differences were observed for peak force between sampling frequencies ($P > 0.05$, Cohen's $d = 0.02$–0.12). A significant difference ($P < 0.001$) was identified in 500, 250 and 100 Hz, with small-moderate and small-large increases in force at set time points and aRFD, respectively, in comparison to 1000 Hz ($d = 0.21$–2.00). Higher sampling frequencies (> 500 Hz) reduces the reliability of time dependent force characteristics, with minimal effect on peak force. Regular monitoring of peak force can be performed with higher sampling frequencies, but lower sampling frequencies would be beneficial to collect reliable rapid-force generating measures.

Keywords Isometric hamstring strength testing · Force plate sampling frequency · Force plate reliability

Introduction

Hamstring strain injuries (HSI) remain one of the most common non-contact muscular strain injuries occurring within team sports in comparison to all other muscle strain injuries [1, 12, 14, 15, 18, 22, 32, 33]. Male and female soccer players experience the highest rates of HSI incidence in comparison to muscle strain injuries (4.99/1000 hours match play and 0.52/1000 hours training [19]) and they have been increasing at a rate of 6.7% between 2014/15 and 2021/22 seasons [19]. This is reported to be related to the proposed primary mechanisms of HSI (i.e., kicking and high-speed running) during match play and training [2, 11]. This was recently confirmed with 61% of all HSIs occurring during running and sprinting movements within elite European soccer between 2001/2002 and 2021/2022 seasons [19], with 88% of hamstring injuries occurring during linear running tasks at median running velocity of 29.28 km/h (26.61–31.13 km/h, interquartile range (IQR)), equating to approximately 87.55% of maximal velocity (78.50%–89.75%, IQR) [23]. During high-speed running, the hamstrings are required to rapidly produce up to 10.5 N/kg in less than 0.10 s to resist the rapid knee extension during the terminal swing phase [9, 20], the point in the running gait cycle during high-speed running where most HSIs occur [2, 11]. Therefore, measures of both peak force and rapid force (such as rate of force development) are able to help practitioners identify deficits in hamstring function that could place the athlete at an elevated risk of injury, as not only is a high force required counteract the swinging shank but it needs to be rapid as the duration to apply the force over is incredibly short.

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Isometric hamstring strength assessments using force plates have been employed to identify changes in strength due to fatigue and identify potential HSI injury risk [3, 4, 21, 29]. A common method of assessing isometric hamstring strength includes force plate technology, which can collect data and provide instant feedback. There are several iterations but the most common being 90° of hip and knee flexion (90–90°) due to ease of application [3, 4 21, 28]. The single leg isometric assessments performed using force plates have been identified as sensitive enough to monitor fatigue using various knee and hip configurations, with around a 11%–24% decrease in isometric hamstring peak force generating capabilities following competitive match play [3, 21], simulated match play [4], and following a standardised repeated sprint protocol [29]. However, as each study has used different methodologies the consensus between them needs exploration. To date only one study has investigated rapid hamstring force development, Bettariga et al. [29] have observed the effect of a repeated sprint protocol on rapid force, finding average rate of force development (aRFD) to be sensitive to fatigue. While this demonstrates the potential benefit of using aRFD to monitor hamstring fatigue, research has not currently investigated how the methods to measure aRFD can be optimised.

As with any new method of assessment, the methods and processes selected for data analysis need to be carefully considered for the assessments to be able to monitor a meaningful change. The effect of sampling frequency of force plate data has been previously examined during the isometric mid-thigh pull [27], demonstrating that sampling frequencies as low as 500 Hz can be used to collect reliable and accurate peak force and time related force metrics. However, during the isometric mid-thigh pull, the entire system mass is on the force plate, making the noise within the force signal very small relative to system mass (i.e., body mass). However, within the 90–90° isometric hamstring assessment the system mass is relatively small, with only the shank and foot registered on the force plate, therefore an increased sampling frequency (e.g., common force plates use 1000 Hz), could have an exponential effect on the reliability and accuracy of peak and time related force metrics. While this could have a large impact on results, it is yet to be explored within the literature.

Hence, the purpose of the present study was to determine the effect of sampling frequency on the 90–90° isometric hamstring assessment, using a force plate, on peak force and time related force metrics. It was hypothesised that peak force would not be adversely affected with increased sampling frequency, in contrast it was hypothesised that time related force metrics (e.g., force at set time points and aRFD) would be decreased at increased sampling frequencies. It was also hypothesised that increased sampling frequencies would have reduced reliability in comparison to lower sampling frequencies for time related force metrics, while having minimal effect on peak force. These hypotheses are based previous observations using multi-joint assessments of force with force plates [27].

Methods

Participants

Thirty-three female elite soccer players from a single club volunteered to participate in the study, all of whom had a minimum of 2-years resistance training experience (age: 18.7 ± 3.7 years; height: 158.3 ± 5.9 cm; body mass: 62.8 ± 5.5 kg). Written informed consent was obtained from all individual participants included in the study and was obtained from the parents where necessary for those under 18 years of age. 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. Ethical approval was granted by the institutional ethics committee (University of Salford, HSR1819-037) in accordance with the 2013 declaration of Helsinki. An *a priori* sample size estimation was conducted, determining that a minimum sample of 25 participants was required to achieve a minimum acceptable statistical power of 80%, with an α error probability of 0.05, a proposed large effect size of 1.2 for the repeated measures analysis of variance (RMANOVA) and a minimum correlation between measures of 0.8. The sample size estimation was calculated using G*Power (Version 3.1, University of Deusseldorf, Germany) [26].

Experimental Design

An observational design was used to determine the effect of force plate sampling frequency on peak force and time specific force metrics obtained during the isometric hamstring strength assessment. Participants completed the tests prior to their normal training day. A familiarization session was carried out two days after a competitive fixture, following their recovery day, with the testing session completed three days after familiarization, allowing at least two days recovery prior to their next competitive fixture.

Isometric Hamstring Testing Protocols

The 90–90° isometric assessments were measured using a force plate (Kistler Type 9286AA: Kistler Instruments Inc, Amherst, NY, USA), collected using Kistler BioWare software. The force plate was 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°). (Fig. 1) The test was conducted unilaterally with the non-testing leg being relaxed and placed fully extended next to the box and arms placed across the chest. Three submaximal trials increasing from 50% to 75% and 90% effort were performed at the end of a standardised warm-up and used as familiarization. Following which three maximal effort trials for each leg were executed with a 60 s rest period allowed between trials. The participants were instructed to drive their heel down into the force platform for approximately 3–5 s, similar to methods used for the isometric mid-thigh pull [5]. Participants were instructed to relax and be as still as possible, without initiating movement for at least one second before the instructions to pull, to permit the calculation of limb weight and associated force-time data including the onset of force production. Participants were required to repeat trials if their hips raised off the ground or if a countermovement was performed, the latter of which was detected through visual inspection of the force trace following each repetition.

Data Analysis

Raw force-time data for each trial was analysed using a customized Microsoft Excel spreadsheet version 2019 (Microsoft Corp., Redmond, WA, USA), force-time data was initially collected at 1000 Hz and during the analysis process was down sampled to 500-, 250-, and 100 Hz, based off previous work on multi-joint assessments [27]. Peak force (N), force at 100- and 200 ms (N) and aRFD (N/s) from onset over a 100- and 200 ms epoch were calculated from the absolute force values for each trial. Peak force was selected as this is the most common metric reported for isometric hamstring assessments, while measures of rapid force were observed due to the specificity of rapid force requirements to HSI incidence and was included in recent

Fig. 1 Visual representation of the 90–90° isometric hamstring assessment

research [29]. Onset of force was identified as 5 standard deviations (SD) from the one second quiet period, based off previous work on multi-joint assessments [16]. The mean values (peak force (N), force at 100- and 200 ms (N) and aRFD (N/s) from onset over a 100- and 200 ms epoch) of the three trials for each limb was taken and averaged (combined left and right limbs) and used for further analysis.

Statistical Analyses

All statistical analyses were conducted using SPSS for Windows version 26 (IBM SPSS Inc, Chicago, IL). Data is presented as the mean ± SD, with normality verified using the Shapiro-Wilk's test ($P > 0.05$). An *a priori* alpha level was set at < 0.05. Within session 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 as the upper 95% CI can be thought of upper error interval. Within session relative reliability was assessed using two-way absolute agreement (3,1) intraclass correlation coefficients (*ICC*) [13, 17, 25, 31]. *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 & Li [31].

A series of repeated measures analyses of variance (RMANOVA) were conducted using SPSS (Version 25; SPSS Inc, IBM, Chicago, Il, USA) to determine if there were significant differences in the Peak force, force at 100- and 200 ms and aRFD over a 100 ms and 200 ms, between sampling frequencies of 1000, 500, 250 and 100 Hz for each variable independently. Post-hoc Bonferroni pairwise comparisons were used to identify if and where any differences in kinetic variables occurred. The magnitude of differences between sampling frequencies for each variable was also calculated using Cohen's *d* effect sizes and interpreted based on the recommendations of Hopkins [10] < 0.20 = trivial and 0.20–0.59 = small, 0.60–1.19 = moderate and ≥ 1.20 = large.

Results

Excellent absolute and good relative reliability was observed for peak force across all sampling frequencies (Table 1; Figs. 2 and 3). Force at 100- and 200 ms and aRFD over 100 ms and 200 ms resulted in mixed relative reliability (Poor to moderate [Table 1; Fig. 2]), and absolute reliability (Poor to excellent [Table 1; Fig. 3]) with a general trend of increasing absolute and relative reliability with decreased sampling frequency (e.g., good to excellent absolute reliability and moderate relative reliability at 250 Hz and 100 Hz [Table 1; Figs. 2 and 3]).

Table 1 Within-session reliability measures for kinetic variables during the 90–90° isometric hamstring assessment across sampling frequencies

Kinetic variable	1000 Hz		500 Hz		250 Hz		100 Hz	
	ICC (95% CI) Interpretation	*CV%* (95% CI) Interpretation	*ICC* (95% CI) Interpretation	*CV%* (95% CI) Interpretation	*ICC* (95% CI) Interpretation	*CV%* (95% CI) Interpretation	*ICC* (95% CI) Interpretation	*CV%* (95% CI) Interpretation
Peak Force	0.90 (0.83–0.94) Good	1.93 (1.71–2.16) Excellent	0.86 (0.76–0.92) Good	1.68 (1.51–1.84) Excellent	0.86 (0.76–0.94) Good	2.03 (1.78–2.28) Excellent	0.88 (0.76–0.93) Good	1.99 (1.75–2.23) Excellent
Force 100 ms	0.64 (0.46–0.79) Poor	7.39 (5.61–9.17) Good	0.68 (0.51–0.91) Moderate	5.46 (4.15–6.78) Good	0.73 (0.55–0.78) Moderate	4.41 (3.34–5.47) Good	0.83 (0.65–0.88) Moderate	3.52 (2.67–4.37) Excellent
Force 200 ms	0.69 (0.53–0.82) Moderate	6.56 (4.98–8.14) Good	0.72 (0.57–0.83) Moderate	5.05 (3.83–6.27) Good	0.74 (0.60–0.85) Moderate	3.58 (2.72–4.45) Excellent	0.84 (0.69–0.95) Moderate	3.34 (2.54–4.15) Excellent
aRFD 100 ms	0.58 (0.42–0.72) Poor	11.69 (8.87–14.51) Moderate	0.65 (0.47–0.80) Poor	7.46 (6.15–8.78) Good	0.68 (0.50–0.83) Moderate	4.91 (3.84–5.97) Good	0.72 (0.56–0.84) Moderate	4.62 (4.01–5.22) Good
aRFD 200 ms	0.63 (0.50–0.78) Moderate	12.45 (9.44–15.45) Poor	0.66 (0.50–0.78) Moderate	9.37 (7.11–11.63) Moderate	0.70 (0.54–0.80) Moderate	6.59 (5.00–8.18) Good	0.75 (0.60–0.87) Moderate	3.99 (3.19–4.80) Excellent

ICC intraclass correlation coefficient, *CV%* coefficient of variation percentage, *CI* confidence interval, *aRFD100 ms* average rate of force over 100 ms, *aRFD200 ms* average rate of force development over 200 ms

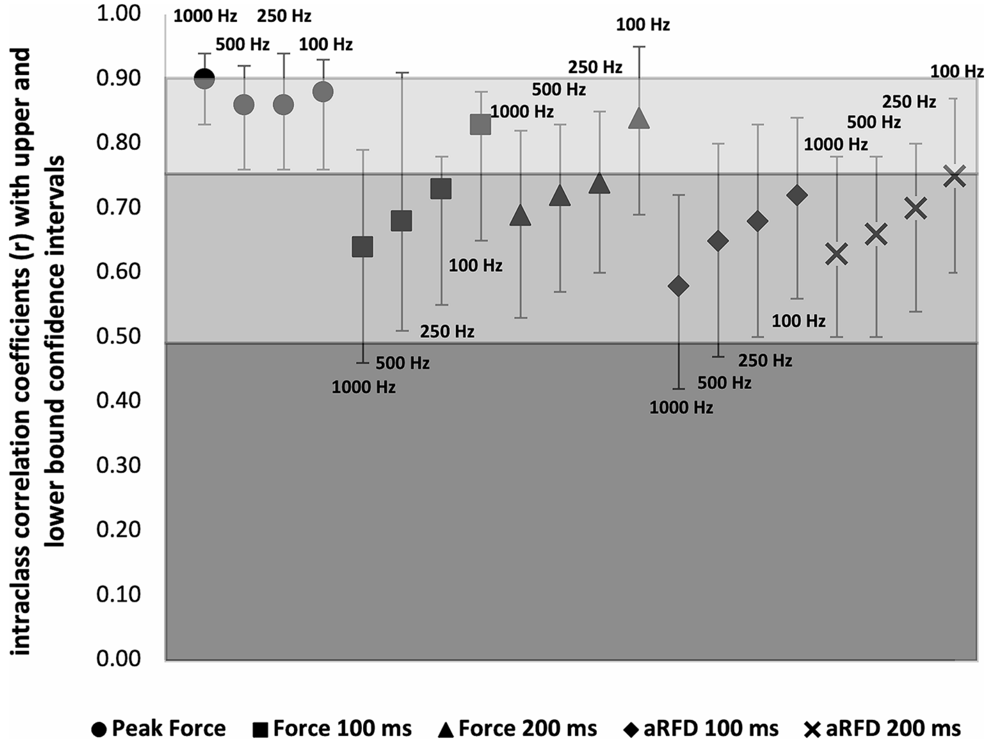

Fig. 2 Visual representation of the relative reliability (*ICC*) and interpretation for all variables

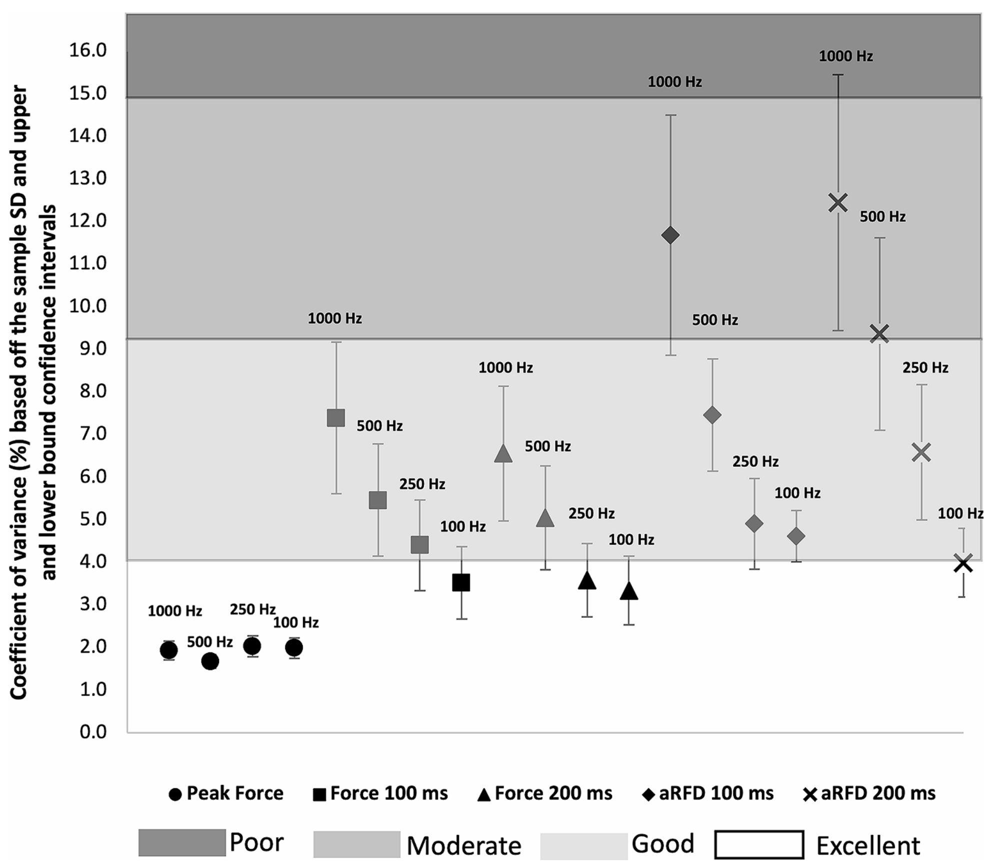

Fig. 3 Visual representation of the absolute reliability (*CV*%) and interpretation for all variables

The results of the RMANOVA revealed no significant differences ($P > 0.05$), with no meaningful changes in peak force between sampling frequencies (Cohen's $d = 0.02$–0.12 (Table 2)). In contrast, the results of the RMANOVA demonstrated a significant difference ($P < 0.001$) in force observed 100 and 200 ms between sampling frequencies. Pairwise comparisons revealed 500, 250 and 100 Hz resulted in small-moderate increases in force at 100 and 200 ms in comparison to 1000 Hz ($d = 0.21$–1.09), with 100 Hz resulting in the greatest mean force at both time points for the three trials (Table 2). Similarly, the results of the RMANOVA also demonstrated a significant difference ($P < 0.001$) in aRFD at 100 and 200 ms between sampling frequencies. Pairwise comparisons revealed 500, 250 and 100 Hz resulted in small-large increases in aRFD to 100 and 200 ms in comparison to 1000 Hz ($d = 0.29$–2.00), with 100 Hz resulting in the greatest aRFD across both time points (Table 2).

Discussion

The aim of the present study was to determine the effect of sampling frequency on the 90–90° isometric hamstring assessment using force plates on peak and time related force metrics and their respective reliability. We hope this information can refine the methods used when researchers and practitioners are collecting isometric hamstring data. In agreement with our hypotheses, peak force was not adversely affected with increased sampling frequency, as there were trivial, non-significant differences between all sampling frequencies and similar absolute and relative reliability values observed. Absolute and relative reliability of time-dependent variables (e.g., force at set time points and aRFD) seem to improve at lower sampling frequencies, although some of the improvements in both absolute and relative reliability seem to be marginal. Despite this, the resulting reliability for sampling at 100 Hz still showed moderate to good relative and good to excellent absolute reliability in time-dependent variables, thus suggesting that sampling at lower frequencies could still provide a reliable measure of time-dependent force variables in the 90–90° isometric hamstring strength assessment. Moreover, there were meaningful mean differences between lower sampling frequencies (100 and 250 Hz) and higher sampling frequencies (500 and 1000 Hz).

The current study highlights there may be improved absolute and relative reliability when measuring aRFD at lower sampling frequencies. All *ICC* and *CV*% variables improved from 1000 Hz to 100 Hz, highlighting the potential benefit of measuring isometric hamstring strength at a lower sampling frequency. The use of lower sampling frequencies may also be useful given reliability of peak force

Table 2 Mean (standard deviation) of kinetic variables and paired differences in kinetic variables for the 90–90° isometric hamstring assessment across sampling frequencies

	1000 Hz		500 Hz		250 Hz		100 Hz	
Kinetic variable	Mean (SD)	Paired differences (*P*) and magnitude (*d*)	Mean (SD)	Paired differences (*P*) and magnitude (*d*)	Mean (SD)	Paired differences (*P*) and magnitude (*d*)	Mean (SD)	Paired differences () and magnitude (*d*)
Peak Force (N)	214.48 (2.03)		214.57 (3.17)		214.41 (4.36)		215.25 (3.30)	-
Force 100 ms (N)	121.48 (9.76)		124.64 (9.82)		126.58 (8.88)		130.41 (7.44)	-
Force 200 ms (N)	147.30 (11.46)		151.64 (7.49)		155.92 (5.04)		157.09 (5.49)	-
aRFD 100 ms (N/s)	1127.50 (81.64)		1158.12 (78.92)		1236.64 (74.47)		1284.04 (74.60)	-
aRFD 200 ms (N/s)	736.50 (76.63)		768.66 (72.03)		789.61 (70.41)		820.46 (67.44)	-

SD standard deviation, *N* Newton, *aRFD100ms* average rate of force development over 100 ms, *aRFD200ms* average rate of force development over 200 ms measures was not sacrificed. However, only one study has previously evaluated the reliability of aRFD on the same test, Bettariga et al., [29] reported similar within session reliability to determine if the measures can be used to assess change for peak force that was identified within the present study. However, aRFD measures within the present study identified improved absolute reliability with worse relative reliability than those reported by Bettariga et al., [29]. Bettariga et al., [29] used a force plate sampling at 1000 Hz, which could explain the poor absolute and moderate relative reliability values presented, as per the results of the present study lower sampling frequencies improved by absolute and relative reliability for rapid force generating metrics. It is worth noting that force at set points within the 90–90° isometric hamstring assessment presents greater absolute and relative reliability than aRFD across all sampling frequencies, this is consistent with observations in multi-joint force plate assessments. Isometric mid-thigh pull measures of aRFD demonstrate lower reliability than force set time points [16, 6]. It is also worth noting that during isometric assessments if force has changed at a set time point, RFD over the same epoch will also have changed to a similar magnitude. The results of the present study could therefore suggest force at set time-points within the 90–90° isometric hamstring assessment being more appropriate than aRFD, with improved reliability and the ability to infer changes in RFD based of changes in force at set time-points.

The present study highlights that sampling frequency does influence the force-time measures during the 90–90° isometric hamstring assessment. Contrastingly, as previously identified, sampling frequency has minimal effect on the isometric mid-thigh pull [27], where the authors concluded that sampling frequencies as low as 500 Hz can be used to collect reliable and accurate peak and time related force metrics. One explanation for the contrasting findings of the present study lies in the difference in system weight between the isometric mid-thigh pull and the 90–90° isometric hamstring assessment, where the system weight of the isometric mid-thigh pull includes entire body mass (aiming to avoid any pre-tension). The 90–90° isometric hamstring assessment only includes shank and foot mass which accounts for only 6.18% of body mass [30]. Therefore, higher sampling frequencies could be impacting the force onset thresholds based off the methods used within the present study, although these are the same to what was used for the isometric mid-thigh pull [27], the lower system mass makes accurate onset identification difficult (Fig. 4). Nyquist's sampling theorem states, to ensure none of the original signal is lost during the sampling process and to prevent aliasing, a sampling frequency of double the highest frequency contained in the signal is necessary [7]. Although this was reported to potentially lose the original signal (i.e., peak values) which has not been identified within the present study, the increased sampling frequency does impact the accurate identification of the onset of force production negatively impacting upon time related metrics as reported in the present study.

The results of this study highlight that a higher sampling frequency has a negative impact on the collection of rapid force generation measures during the 90–90° isometric hamstring assessment. Impacting both reliability and the values observed for rapid force, while having minimal effect on peak force generating capabilities. Based on the current literature peak force and rapid force generating measures (aRFD) showed similar capacity to identify neuromuscular fatigue using isometric hamstring assessments using force plates (including the 90–90° isometric test) which have been found to be sensitive enough to detect fatigue with 11%–24% decreases peak force identified [3, 4, 21, 29]. Bettariga et al., [29] has demonstrated aRFD has a similar degree of

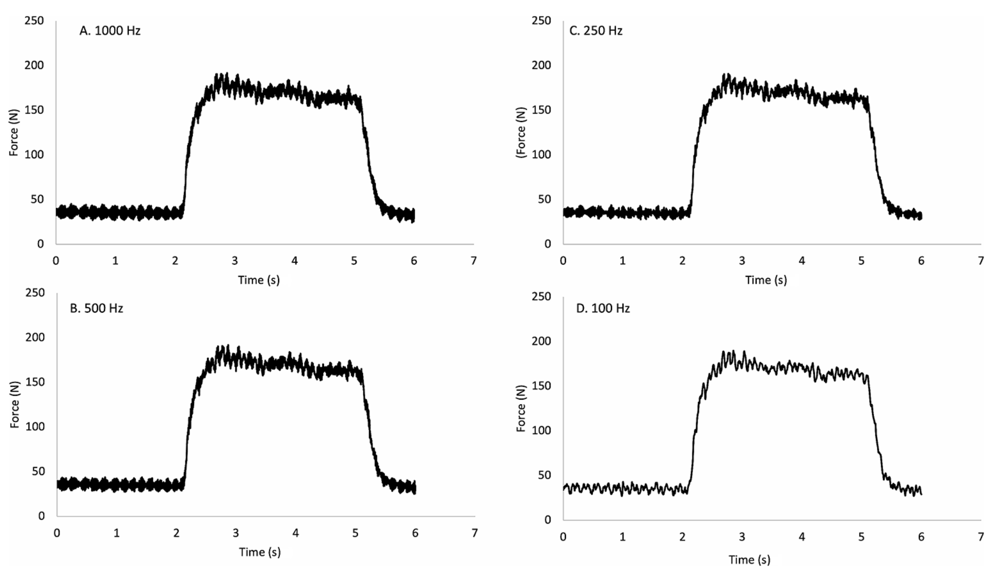

Fig. 4 Example force-time traces at (A) 1000-, (B) 500-, (C) 250- and (D) 100 Hz for the 90–90° isometric hamstring assessment highlighting the effect of over sampling

sensitivity to fatigue as peak force, however based on the findings of the current study results may vary if a lower sampling frequency is used. This warrants further investigation to the sensitivity of rapid force generating measures at varying sampling frequencies. Research is also necessary to identify how much the decreases observed in peak force under fatigue can explain any associated decreases in rapid force generating measures. This may be possible by reporting the change in peak force in addition to the change in time related variables (e.g., force at specific time-point, or RFD over specific epochs) as a percentage of peak force [8, 24, 34]. Moreover, further work is required to establish the practical implications of reduced isometric hamstring force assessed using force plates as a result of fatigue, such as any relationship with HSI incidence which is current missing within the literature.

This study is not without its limitations. Firstly, the sample was on female soccer players who would arguably have reduced skeletal muscle mass than other population which could be exaggerating the issue with oversampling and reduced accuracy of the onset methodology. However, despite the homogeneity within the sample (sex, age, sport and playing level) they all had familiarity with the testing procedures with > 2 years resistance training experience. Secondly, only a single method of onset identification was used specifically onset of force was identified as 5 SD from the one second quiet period, which is based on the recommendations on the isometric mid-thigh pull when aiming to observe time specific force values [16]. To date no study has identified the onset threshold used when performing the 90–90° isometric hamstring assessment [3, 4, 21, 28, 29]. Therefore, further investigation is required to determine the most accurate and reliable method of determining force onset within the 90–90° isometric hamstring assessment and other isometric hamstring assessments using force plates, including standing 90° of hip flexion and 20° of knee flexion (90–20°) assessment and the 30° of hip and knee flexion (30–30°) assessment where these results will likely transfer over.

Conclusions

Overall, the results of this study demonstrate that a higher sampling frequency reduces the reliability of time dependent force characteristics during the 90–90° isometric hamstring assessment, while having minimal effect on the peak force observed. Good-excellent absolute and relative reliability was observed for peak force across all sampling frequencies, while rapid-force generating characteristics displayed poor-excellent absolute and relative reliability with improved reliability typically observed as lower sampling frequencies (100–250 Hz). Therefore, if practitioners and scientists are only observing measures of peak force then any sampling frequency can be utilised, but lower sampling frequencies would be beneficial if practitioners and scientists want to collect more reliable rapid-force generating measures (force values at 100 and 200 ms and aRFD up to 100 and 200 ms). Practitioners and researchers should look to down sample data collected on 90–90° isometric hamstring assessment if wanting to monitor rapid force production characteristics. It is also likely these findings transfer over to other assessments including the 90–20° and 30–30° isometric hamstring assessments, but further investigation is required. However, as more commercially available wireless force plate devices with automatic analysis software enter the sports-technology market, developers should look to add options to reduce the sampling frequency to allow for the accurate and reliable collection of time related force generating measures or allow for raw data to be exported for further analysis (i.e. down sampling), although further investigation is required to determine the importance of rapid-force generating measures in monitoring and tracking athletic performance over and above peak force alone.

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Data Availability Data will be made available on reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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