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THE EFFECT OF DIFFERENT ONSET THRESHOLDS ON ISOMETRIC HAMSTRING FORCE-TIME VARIABLES USING FORCE PLATES

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ABSTRACT

Introduction. There is an increasing frequency of single joint isometric assessments using force plates within team sports to inform training decisions; however, limited methodological consistency has been identified within the literature, including onset threshold (muscle contraction initiation). Purpose: The purpose of this study was to determine the effect of different onset thresholds on force-time characteristics during a 90:90 isometric hamstring assessment. Methodology: Twenty female soccer players (age: 20.7 ± 4.7 years; height: 168.7 ± 5.9 cm; body mass: 64.4 ± 6.7 kg) completed three maximal trials per limb. Five thresholds assessed, including five standard deviations (SD) of system weight (SW, which included limb weight and any pre-tension) (SW_{5SD}), SW plus 15 N (SW_{15N}), and 10-, 20-, and 30% of SW. Results: Moderate relative reliability and excellent absolute reliability for force at 100 ms (F100) and 200 ms (F200), and rate of force development (RFD) was observed for SW_{5SD} and SW_{15N}, outperforming percentage-based thresholds. 10-, 20- and 30% of SW resulted in increased F100, F200, and RFD values, with large effects observed ($\eta^2_p \geq 0.166$). Conclusions: SW_{5SD} and SW_{15N} were identified as the most reliable and consistent methods for assessing time-related force variables. Practical implications: Sport scientists, strength and conditioning coaches, and medical staff who regularly use isometric hamstring assessments to monitor training and return to sport objectives are recommended to use either SW_{5SD} and SW_{15N} thresholds to ensure valid and accurate results on the hamstrings force generating that can be used to inform training.

Keywords: *rapid force, rate of force development, fatigue, return to sport*

INTRODUCTION

According to the results of a recent sur– vey > 50% of practitioners in professional men's soccer use force plates (Weldon et al., 2020), with recommendations to use these for benchmarking, fatigue monitoring, and rehabilitation (Bishop et al., 2022). Commonly, force plate testing has included dynamic and isometric multi-joint assessments (Bishop et al., 2022; Comfort et al., 2019); however, more recently, with the increased availability of wireless force plate technology, single-joint isometric tasks are becoming commonplace (Constantine et al., 2019; Cuthbert et al., 2021; Matinlauri et al., 2019; McCall et al., 2015; McMahon et al., 2023; Moreno-Perez et al., 2020; Ripley et al., 2023). This increased technology availability enables rapid, non-fatiguing isometric assessments to be performed. Moreover, this allows for a single piece of technology to be used for multiple dynamic and isometric tests without relying on several pieces of technology to assess athletes in dynamic and isometric tasks, maximizing portability. Within soccer, muscle strain injuries, specifically hamstring strain injuries, continue to be the most prevalent injury (Ekstrand et al., 2023; Maniar et al., 2023). As such, it has been recommended that practitioners evaluate eccentric hamstring strength to categorize risk

(Opar et al., 2021; Opar et al., 2015; Timmins et al., 2016). However, the uptake of the Nordic hamstring exercises, used to assess and develop eccentric hamstring strength, remains low (Ekstrand et al., 2022; Ekstrand et al., 2023). Moreover, as regular performance monitoring should be implemented, ensuring that no additional increase in muscle soreness can be seen is essential. Therefore, isometric tasks could be preferred for monitoring purposes due to the reduced chance of muscle soreness and quicker assessment process.

Multiple iterations of isometric hamstring assessments have been used within the literature and practice (Bettariga et al., 2023; Constantine et al., 2019; Cuthbert et al., 2021; Matinlauri et al., 2019; McCall et al., 2015; Moreno-Perez et al., 2020; Ripley et al., 2023; Ripley et al., 2024; Taberner & Cohen, 2018), including a variety of setups and joint positions, ultimately affecting muscle-tendon unit lengths and therefore force production capability. The most frequently investigated isometric hamstring assessment is the 90:90 assessment (Constantine et al., 2019; Matinlauri et al., 2019; McCall et al., 2015; Ripley et al., 2023; Ripley et al., 2024), where the hip and knee angles are both set at 90°. This position is suggested to favor the medial portion of the hamstrings (Onishi et al., 2002; Read et al., 2019), specifically semitendinosus and semimembranosus, although, as the intention should be for knee flexion, both medial and lateral components of the hamstrings will be activated during the task. Other variations include the 30:30 and 90:20 (Constantine et al., 2019; Matinlauri et al., 2019; McCall et al., 2015), where the hip and knee joints are set to 30° of hip and knee flexion and 90° of hip flexion and 20° of knee flexion, respectively. As each of these variations will likely impact the tension placed upon the hamstrings, for example with the 90:20 isometric placing the hamstrings at the greatest muscle tension there will likely be increased system weight (i.e., the mass of the limb and muscle tension applied prior to the start of the test) and potentially increased variability in some athletes such as team sport athletes who possess tight hamstrings (Cejudo et al., 2021). This increased variability, through an inability to remain still or the potential of shifts in vertical and horizontal force (Rasp et al., 2024), could impact accurate identification of the onset of force production, which is essential for accurate assessment of time-related force-time characteristics (Dos'Santos et al., 2017).

Isometric hamstring assessments have been consistently used to monitor hamstring „*readiness*" across the literature. Peak force has been consistently reported to be reduced following a fatiguing activity (Bettariga et al., 2023; Constantine et al., 2019; Matinlauri et al., 2019; McCall et al., 2015), highlighting the sensitivity of such tests in all testing positions. However, Rapid force has the potential for diverging characteristics among athletes, specifically in their ability to apply force rapidly (Barber et al., 2024), highlighting the need to observe rapid force measures. Therefore, peak force alone might not provide a true representation of fatigue-induced changes in hamstring force-generating characteristics and thus the manifestation of fatigue. To date, researchers have only reported the effect of a fatiguing activity on rapid force measures in two studies (Bettariga et al., 2023; Cosio et al., 2024). Bettariga et al. (2023) observed a greater magnitude of change within RFD ($g = 1.37$) in comparison to peak ($g = 1.33$) for the non-dominant limb (Bettariga et al., 2023), highlighting the need to observe measures of rapid force accurately. In order to identify measures of rapid force production, including RFD, the onset of force production needs to be accurately identified (Dos'Santos et al., 2017). Using a threshold of 5 standard deviations (SD) from a stable weighing period of system weight (SW) has also been shown to be the most accurate for collecting force-time specific and RFD measures within multi-joint isometric assessments such as the mid-thigh pull (Dos'Santos et al., 2017; Guppy et al., 2024). However, other thresholds could be more appropriate due to variability and the lower absolute system weight during single joint isometric testing. To date, no study has looked to determine an optimal onset threshold calculation for any single joint isometric assessment.

With the increasing frequency of single joint isometric force assessment in soccer for benchmarking and monitoring purposes, identifying the optimal data analysis methods is crucial for practitioners to make objective decisions on the training process. Currently, there is no consensus on the optimal method of identifying the onset of force within a single joint isometric hamstring assessment, which would be imperative for measures of rapid force. Therefore, the purpose of this study was to determine the effect of different onset thresholds on force-time characteristics assessed within the 90:90 isometric hamstring assessment using force plates. It was hypothesized that using five SDs from SW (SW_{5SD}) would provide the most accurate and reliable method for determining onset threshold for the identification of force-time specific and RFD measures within the 90:90 assessment isometric hamstring assessment, in comparison to other absolute and relative onset thresholds.

METHODS

Experimental design

An observational cross-sectional research design was used to determine the effect of varying force onset thresholds on the 90:90 isometric hamstring strength assessment on a single test occasion, determining the effect of different onset thresholds across three trials performed. Based on the work of Borg et al. (2022), and previously identified intraclass correlation coefficient (*ICC*) values for this test (Ripley et al., 2024), an expected *ICC* of $> .80$, an alpha error probability $p < .05$ and statistical power of 80%, a required sample of 33 was identified to determine the reliability of the methods. To determine the difference between onset thresholds, with an alpha error probability $p < .05$, statistical power of 80%, and an effect size f of 0.27 (Ripley et al., 2024), a minimum sample of 15 was required. The sample size estimations were calculated using G*Power (Version 3.1, University of Düsseldorf, Germany) (Faul et al., 2007).

Participants

Twenty female soccer players with 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, Tier 3-4 as suggested by McKay et al. (2022), volunteered to participate in the study. Each limb was taken as an independent sample ($n = 40$), which enabled the reliability aspect of the study. 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 the study. Ethical approval was granted by the University of Salford institutional ethics committee (HSR1819-037) in accordance with the Declaration of Helsinki 2013. Participants completed the tests prior to their regular training day, following a standardized warm-up including two sets of 10 repetitions of squats, lunges, hamstring stretches, leg swings, and calf raises. A familiarization session was carried out 48 hours after a competitive fixture, with the testing session completed three days after familiarization.

90:90 Isometric hamstring test description

Force-time data during 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. 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, only their heel resting on the force plate with footwear removed 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 between 3–5 s, following three submaximal trials using identical methods; each trial was collected by the same practitioner who was an accredited strength and conditioning coach with experience in administering force plate assessments. Between maximal trials, 60 seconds of rest was provided between efforts. Participants were instructed to remain as still as possible, without initiating a movement for at least a 1-second period to permit the calculation of system weight (SW [i.e., the weight of the limb]) and associated force-time data, including onset, before the instructions to '*pull hard and fast*'. Participants were required to repeat trials if their hips raised off the ground for either the contralateral or ipsilateral side, 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.

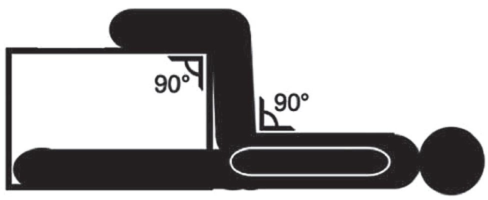

Figure 1. *90:90 Isometric Knee Flexor Test*

Data analysis

Raw force-time data for each trial were analysed using a customized Microsoft Excel spreadsheet (version 2019, Microsoft Corp., Redmond, WA, USA). Initially, force-time data sampled at 1000 Hz was filtered to 250 Hz based on the recommendations from Ripley et al. (2024) when using the isometric hamstring assessment.

Peak force, force at 100 ms (F100), force at 200 ms (F200) and the average rate of force development (RFD) from 0-200 ms were calculated from the net force values (excluding limb weight established from the one second initial weighing period) for each trial calculated via dividing force at 200 ms by 0.2 s. The mean of the three trials was taken and used for further analysis when determining mean differences between onset threshold and associated rapid force metrics, as this accounts for natural variation and minimizes the effect of random errors.

Five different onset thresholds were implemented and compared to explore the effects of different onset thresholds on 90:90 isometric force-time variables. The criteria onset threshold and onset of the contraction (referred to as time point 0 ms) were defined as force exceeding five SDs from SW (SW_{5SD}). The other onset thresholds were compared against the criterion method and were defined as point when (a) force exceeded 10% from SW (SW_{10}), (b) force exceeded 20% from SW (SW_{20}), (c) force exceeded 30% from SW (SW_{30}), and (d) force exceeded 15 N from SW (SW_{15N}). The combined residual force and SW were calculated as the average force over a 1-second stationary weighing period before the initiation of the 90:90 isometric assessment, similar to the weighing period calculations of SW during vertical jump (McMahon et al., 2018; McMahon et al., 2019) and isometric multi-joint strength assessments (Dos'Santos et al., 2017; Guppy et al., 2024).

Statistical analyses

All within reliability (i.e., reliability across three trials within the same session) analysis was performed across the three trials, where 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 % (excellent), 5−9.99% (good), 10−14.99% (moderate) and > 15% (poor), respectively. Relative reliability was assessed using two-way absolute agreement (3,1) *ICC* (Koo & Li, 2016; McGraw & Wong, 1996; Shrout & Fleiss, 1979), ICC values were interpreted based on the lower bound 95% *CI* (*ICC*; poor < .49, moderate .50−.74, good .75−.89 and excellent > .90) as suggested by Koo & Li (2016).

Data were initially pooled for each limb and are presented as the mean ± SD. Normality was verified using the Shapiro-Wilk test. An *a priori* alpha level was set at < .05. The mean of the difference (bias) was expressed absolutely and as a percentage, ratio (criterion method/alternative method), 95% limits of agreement (*LOA*) (*LOA*: mean of the difference ± 1.96 standard deviations) and 95% *CI* were calculated between onset threshold methods using the methods described by Bland and Altman (1986). Unacceptable *LOA* were set *a priori* as bias percentage greater than ± 5%.

A series of one-way analyses of variance (*ANOVA*) with Bonferroni post-hoc comparisons, bootstrapped to 10,000 samples (Efron, 1987), were conducted to determine whether there were significant differences between the different onset thresholds for the onset threshold, F100, F200, and RFD. Statistical significance was defined as $p \leq .05$ for all tests, with resultant *p* values corrected, using Bonferroni correction, to reduce the risk of a family-wise error. The magnitude of differences within the one-way analysis of variance was also calculated using Partial eta squared (η^2_p) interpreted as < .01 (trivial), .01−.06 (small), .07−.13 (medium) and > .14 (large effect), while pairwise Cohen's d effect sizes and interpreted based on the recommendations of Hopkins (2002) .00−.19 (*trivial*) and .20−.59 (small), .60−1.19 (moderate) and > 1.20 (large). All statistical analyses were conducted using JASP (Version 0.19.0, computer software).

RESULTS

Within session reliability, mean ± between-trial *SD* values are presented in Table 1. Both SW_{5SD} and SW_{15N} demonstrated moderate relative reliability for all variables, with excellent absolute reliability observed for the onset threshold and F100 and F200, but only good absolute reliability for RFD 0−200 ms. In contrast, SW_{10}, $SW_{20,}$ and SW_{30} resulted in poor to moderate relative reliability and good to excellent absolute reliability.

Table 1. *Mean ± SD between trial values and within session reliability for onset threshold and measures of rapid force for each method of determining onset.*

		SW_{5SD}	**SW_{10}**	**SW_{20}**	**SW_{30}**	**SW_{15N}**
Onset threshold (N)	*Mean ± SD*	56.09 ± 1.03	41.36 ± 1.42	45.12 ± 1.55	48.88 ± 1.68	52.60 ± 1.29
	CV% (95% *CI*)	1.83 (1.43 – 2.24)	3.43 (2.68 – 4.19)	3.72 (2.92 – 4.50)	3.85 (3.01 – 4.78)	2.45 (1.92 – 2.99)
	ICC (95% *CI*)	.753 (.623 – .865)	.671 (.545 – .777)	.691 (.555 – .787)	.713 (.578 – .792)	.719 (.576 – .813)
Force at 100 ms (N)	*Mean ± SD*	118.16 ± 2.85	70.06 ± 5.91	91.63 ± 3.19	102.71 ± 3.03	111.91 ± 2.93
	CV% (95% *CI*)	2.36 (1.84 – 2.88)	8.43 (6.58 – 10.28)	6.48 (4.71 – 8.24)	5.95 (3.30 – 7.59)	2.62 (2.05 – 3.20)
	ICC (95% *CI*)	.728 (.617 – .819)	.404 (.241 – .566)	.591 (.449 – .717)	.590 (.448 – .717)	.656 (.526 – .767)
Force at 200 ms (N)	*Mean ± SD*	150.68 ± 2.89	97.63 ± 6.72	125.99 ± 5.88	135.95 ± 7.49	146.14 ± 3.87
	CV% (95% *CI*)	1.92 (1.31 – 2.51)	6.88 (4.75 – 9.01)	4.66 (3.22 – 6.11)	5.51 (3.80 – 7.21)	2.65 (1.83 – 3.47)
	ICC (95% *CI*)	.695 (.575 – .796)	.332 (.168 – .502)	.530 (.379 – .670)	.509 (.356 – .653)	.660 (.531 – .769)
RFD 0-200 ms (N/s)	*Mean ± SD*	753.42 ± 14.45	488.17 ± 33.58	629.97 ± 29.38	679.73 ± 37.43	730.72 ± 19.36
	CV% (95% *CI*)	3.84 (2.65 – 5.02)	9.88 (7.73 – 12.13)	9.66 (8.54 – 11.63)	9.51 (7.52 – 11.28)	6.53 (5.34 – 8.26)
	ICC (95% *CI*)	.695 (.575 – .796)	.332 (.168 – .502)	.430 (.279 – .570)	.512 (.357 – .655)	.660 (.531 – .769)

RFD = average rate of force development, SD = Standard deviation, CV% = coefficient of variation percentage, CI = confidence interval, ICC = intra-class correlation coefficient, SW = system weight

SW_{10} resulted in the lowest onset threshold, with a progressive increase as the percentage of system weight increased, with similar trends observed for time-related force variables (Table 1). A large overall effect ($\eta^2_P \geq 0.166$) was observed between the methods for determining the onset of force for the onset thresholds, F100, and F200. In contrast, only a medium overall effect ($\eta^2_P = 0.139$) was observed for RFD 0-200 ms (Table 2). Small-large differences as determined via Cohen's *d* effect sizes were observed for the onset threshold value between methods, with trivial-large differences between onset threshold methods for F100 and F200, and trivial-moderate differences were identified between RFD 0–200 ms.

Table 2. *Cohen's d pairwise differences (95% confidence interval) between onset threshold methods for the onset threshold and rapid force characteristics.*

	SW_{5SD}	SW_{10}	SW_{20}	SW_{30}
Onset threshold (N)	SW_{10} = 1.45 (0.77–2.14) SW_{20} = 1.09 (0.42–1.76) SW_{30} = 0.72 (0.06–1.38) SW_{15N} = 0.32 (-0.34–0.97)	SW_{20} = 0.37 (-0.29–1.02) SW_{30} = 0.74 (0.08–1.40) SW_{15N} = 1.13 (0.47–1.81)	SW_{30} = 0.37 (-0.29–1.02) SW_{15N} = 0.77 (0.11–1.43)	SW_{15N} =0.40 (-0.25-1.06)
Force at 100 ms (N)	SW_{10} = 1.39 (0.71–2.08) SW_{20} = 0.73 (0.07–1.39) SW_{30} = 0.42 (-0.24–1.07) SW_{15N} = 0.15 (-0.50–0.81)	SW_{20} = 0.66 (0.01–1.32) SW_{30} = 0.98 (0.31–1.64) SW_{15N} = 1.24 (0.56–1.92)	SW_{30} = 0.31 (-0.34–0.97) SW_{15N} = 0.57 (-0.08-1.23)	SW_{15N} = 0.26 (-0.39-0.92)
Force at 200 ms (N)	SW_{10} = 1.24 (0.56–1.92) SW_{20} =0.54 (-0.12–1.20) SW_{30} = 0.32 (-0.34–0.97) SW_{15N} = 0.11 (-0.54–0.76)	SW_{20} = 0.70 (0.04–1.36) SW_{30} = 0.92 (0.26–1.59) SW_{15N} = 1.13 (0.46–1.80)	SW_{30} = 0.22 (-0.43–0.88) SW_{15N} = 0.43 (-0.23-1.09)	SW_{15N} = 0.21 (-0.45-0.86)
RFD 0–200 ms (N/s)	SW_{10} = 1.14 (0.48–1.80) SW_{20} = 0.57 (-0.08–0.57) SW_{30} = 0.34 (-0.30–0.98) SW_{15N} = 0.14 (-0.49–0.78)	SW_{20} = 0.57 (-0.07–1.80) SW_{30} = 0.80 (0.15–1.44) SW_{15N} = 0.99 (0.35–1.64)	SW_{30} = 0.23 (-0.41–0.86) SW_{15N} = 0.42 (-0.21-1.06)	SW_{15N} = 0.20 (-0.83-0.42)

RFD = average rate of force development, SW = system weight, SW_{5SD} = 5 standard deviations of system weight, SW_{10} = 10% of system weight, SW_{20} = 20% of system weight, SW_{30} = 30% of system weight, SW_{15N} = System weight plus 15 N

The relative percentage thresholds (SD_{10}, SD_{20} & SD_{30}) resulted in lower F100, F200 and RFD in comparison to SD_{5SD} and SD_{15N} (Figure 2).

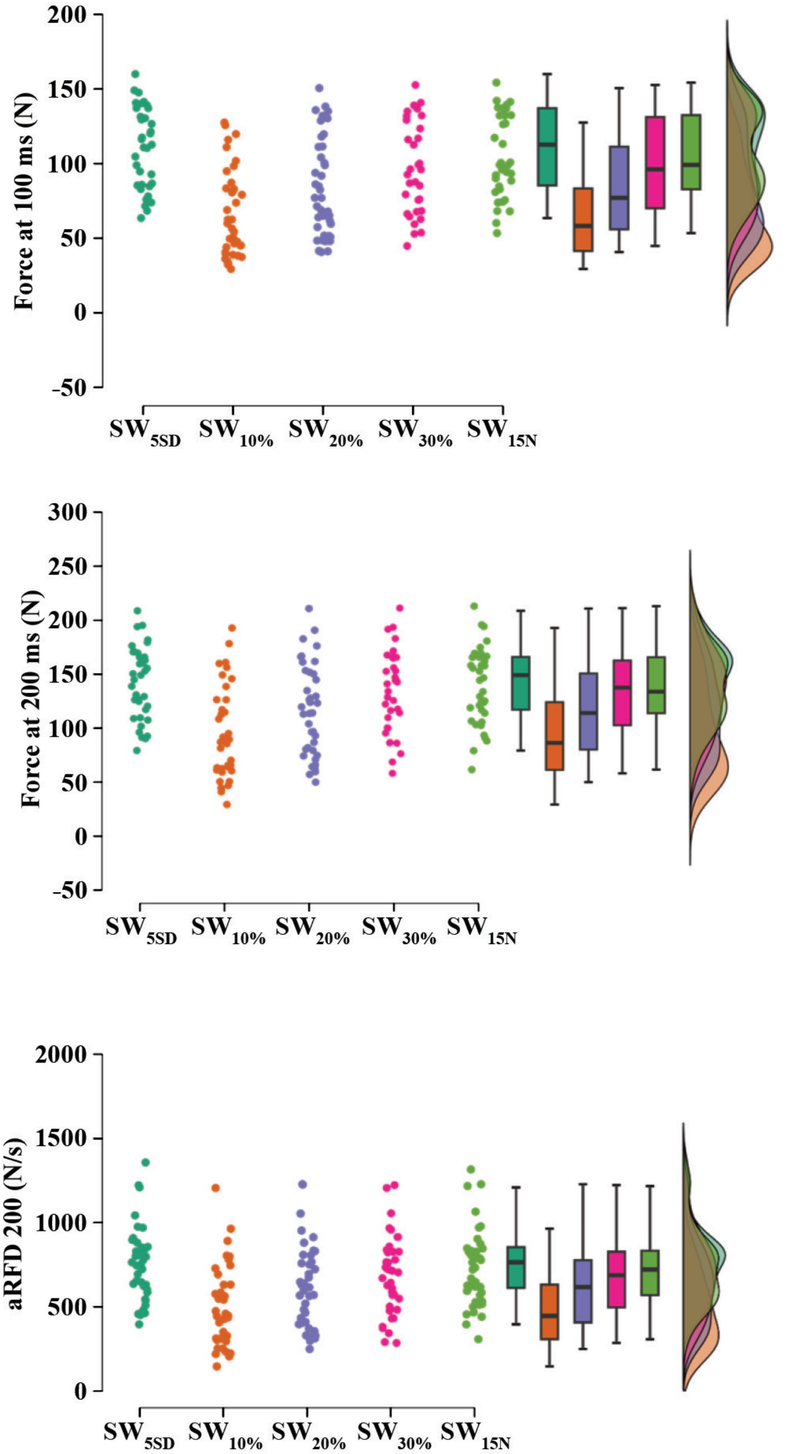

Figure 2. *A combined raincloud plot shows the difference in rapid force-generating characteristics between onset threshold methods.*

Unacceptable bias (95% *LOA* > 5%) was observed for all comparisons apart from SW_{5SD} vs. SW_{30}, SW_{5SD} vs. SW_{15N}, and SW_{30} vs. SW_{15N} for RFD 0-200 ms (Table 3).

Table 3. *Bias and limits of agreement between the methods of onset threshold identification.*

Comparison		SW_{5SD} vs SW_{10}	SW_{5SD} vs SW_{20}	SW_{5SD} vs SW_{30}	SW_{5SD} vs SW_{15N}	SW_{10} vs SW_{20}	SW_{10} vs SW_{30}	SW_{10} vs SW_{15N}	SW_{20} vs SW_{30}	SW_{20} vs SW_{15N}	SW_{30} vs SW_{15N}
Onset Threshold (N)	**Bias (95% *CI*)**	14.42 (13.66 to 15.18)	10.81 (9.93 to 11.70)	7.20 (6.13 to 8.26)	3.03 (2.30 to 3.76)	-3.61 (-3.88 to -3.33)	-7.22 (-7.78 to -6.67)	-11.39 (-11.67 to -11.11)	-3.62 (-3.89 to -3.34)	-7.78 (-8.33 to -7.23)	-4.17 (-4.99 to -3.34)
	95% upper bound *LOA* (95% *CI*)	18.90 (17.58 to 20.22)	16.01 (14.48 to 17.54)	13.45 (11.61 to 15.39)	7.33 (6.06 to 8.60)	-1.99 (-2.46 to 1.51)	-3.99 (-4.94 to -3.04)	-9.76 (-10.24 to -9.28)	-2.00 (-2.48 to -1.53)	-4.53 (-5.49 to -3.57)	0.699 (-0.73 to 2.132)
	95% lower bound *LOA* (95% *CI*)	9.94 (8.62 to 11.26)	5.62 (4.08 to 7.15)	-0.94 (-0.91 to 2.78)	-1.27 (-2.54 to 0.00)	-5.23 (-5.71 to -4.75)	-10.46 (-11.41 to -9.51)	-13.02 (-13.50 to -12.54)	-5.23 (-5.71 to -4.76)	-11.03 (-11.99 to – 10.76)	-9.03 (-10.46 to – 7.60)
F100 (N)	**Bias (95% *CI*)**	45.31 (38.98 to 51.64)	24.87 (19.39 to 30.35)	14.20 (10.29 to 18.11)	5.11 (3.07 to 7.14)	-20.44 (-26.28 to -14.59)	-31.11 (-37.17 to -25.05)	-40.20 (-46.79 to -33.62)	-10.67 (-14.80 to -6.55)	-19.77 (-24.88 to 14.65)	-9.10 (-12.35 to -5.84)
	95% upper bound *LOA* (95% *CI*)	82.52 (71.55 to 93.48)	57.08 (47.59 to 66.57)	37.19 (30.41 to 43.96)	17.08 (13.55 to 20.60)	13.92 (3.79 to 24.04)	4.53 (-5.97 to 15.04)	-1.50 (-12.91 to 9.90)	13.57 (6.43 to 30.72)	10.29 (1.43 to 19.15)	10.05 (4.41 to 15.69)
	95% lower bound *LOA* (95% *CI*)	8.10 (-2.86 to 19.06)	-7.34 (16.83 to 2.15)	-8.79 (-15.56 to -2.01)	-6.87 (-10.39 to 3.34)	-54.79 (-64.91 to -44.67)	-66.75 (-77.25 to -56.25)	-78.90 (-90.31 to -67.50)	-34.92 (-42.06 to -27.78)	-49.83 (-58.68 to -40.97)	-28.24 (-33.88 to 22.60)
F200 (N)	**Bias (95% *CI*)**	49.93 (40.08 to 59.78)	23.24 (15.82 to 30.65)	13.52 (8.32 to 18.73)	4.77 (1.93 to 7.60)	-26.69 (-33.19 to -20.19)	-36.41 (-44.44 to -28.37)	-45.17 (-54.53 to -35.80)	-9.71 (-14.11 to -5.32)	-18.47 (-25.07 to -11.87)	-8.76 (-13.07 to -4.45)
	95% upper bound *LOA* (95% *CI*)	107.85 (90.78 to 124.92)	66.84 (53.99 to 79.68)	44.13 (35.11 to 53.15)	21.41 (16.51 to 26.32)	11.53 (0.27 to 22.79)	10.85 (-3.07 to 24.78)	9.89 (-6.33 to 26.11)	16.13 (8.51 to 23.74)	20.33 (8.90 to 31.77)	16.58 (9.12 to 24.05)
	95% lower bound *LOA* (95% *CI*)	-7.99 (-25.06 to 9.08)	-20.36 (-33.21 to -7.51)	-17.08 (-26.10 to -8.07)	-11.88 (-16.79 to -6.98)	-64.91 (-76.17 to -53.65)	-83.66 (-97.58 to -69.74)	-100.22 (-116.44 to -83.99)	-35.56 (-43.17 to -27.94)	-57.28 (-68.71 to -45.85)	-34.10 (-41.57 to -26.63)
RFD200 (N)	**Bias (95% *CI*)**	30.19 (13.33 to 47.06)	18.55 (4.88 to 32.22)	7.87 (3.02 to 13.73) **	3.65 (0.63 to 6.67) **	-11.64 (-16.19 to -7.09)	-22.32 (-36.96 to -7.68)	-26.55 (-41.92 to -11.17)	-10.68 (-21.93 to 0.58)	-14.90 (-26.94 to -2.86)	-4.23 (-6.79 to -1.66) **
	95% upper bound *LOA* (95% *CI*)	129.33 (100.12 to 158.54)	98.93 (75.24 to 122.60)	36.42 (28.01 to 44.84) **	21.40 (16.17 to 26.63) **	15.07 (7.20 to 22.94)	63.77 (38.40 to 89.13)	63.83 (37.20 to 90.46)	55.48 (35.99 to 74.97)	55.87 (35.02 to 76.72)	10.88 (6.43 to 15.34)
	95% lower bound *LOA* (95% *CI*)	-69.94 (-98.15 to -39.73)	-61.82 (-85.51 to -38.14)	-20.68 (-29.09 to -12.27) **	-14.11 (-19.34 to -8.88) **	-38.36 (-46.23 to -30.49)	-108.41 (-133.77 to -83.04)	116.92 (-143.55 to -90.30)	-76.83 (-96.32 to -57.34)	-85.67 (-106.53 to -64.82)	-19.34 (-23.79 to -14.89) **

*** Acceptable bias between onset threshold calculations; CI = confidence interval; LOA = limit of agreement, SW_{5SD} = 5 standard deviations of system weight, SW_{10} = 10% of system weight, SW_{20} = 20% of system weight, SW_{30} = 30% of system weight, SW_{15N} = System weight plus 15 N*

DISCUSSION

The purpose of this study was to determine the effect of different onset thresholds on force-time characteristics assessed within the 90:90 isometric hamstring assessment using force plates. The hypothesis can be accepted, as meaningful differences were observed in the onset threshold and measures of rapid force (F100, F200, and RFD) when using different methods of identifying onset. The criterion method, SW_{5SD}, resulted in the greatest onset threshold value, while 10% of SW was the smallest onset threshold value. These differences resulted in small to large differences in measures of rapid force. Absolute and relative reliability were also impacted by the onset threshold method used; excellent absolute and moderate relative reliability were observed for the onset threshold value. Excellent-good absolute reliability was seen for all measures of rapid force for SW_{5SD} and SW_{15N}, whereas good-moderate absolute reliability was observed for SW_{10}, $SW_{20,}$ and SW_{30}. Similarly, SW_{5SD} and SW_{15N} had the greatest relative reliability, with moderate reliability observed for all, while only poor reliability was observed for SW_{10}, $SW_{20,}$ and SW_{30} methods. When comparing between the methods onset identification, unacceptable bias (95% *LOA* > 5%) was observed for all comparisons apart from SW_{5SD} vs. SW_{30}, SW_{5SD} vs. SW_{15N}, and SW_{30} vs. SW_{15N} for RFD 0–200 ms, this could be explained by these methods resulting in the greatest onset threshold values in comparison to SW_{10}, SW_{20}.

Peak force has most frequently been reported within isometric assessments of the hamstrings when using force plate technology, however, as a strong relationship has recently been observed between peak force and rapid force (Ripley et al., 2023), with the potential for diverging characteristics among athletes when rapid force is made relative to peak force (*fast and strong, fast and weak, slow and strong, slow and weak*) (Barber et al., 2024). Hence, despite being useful in monitoring neuromuscular function, observations of peak force alone might not provide a true representation of fatigue-induced changes (Barber et al., 2024). Moreover, the potential injury occurrence within 200 ms of ground contact during sprinting also provides a rationale to observe these rapid time points (Heiderscheit et al., 2005). Rapid force has been assessed in several studies, the majority of researchers using the SW_{5SD} for identification of the onset (Barber et al., 2024; Ripley et al., 2023; Ripley et al., 2024; Ripley et al., 2024), citing this method as the most appropriate in multi-joint isometric tasks (McMahon et al., 2018; McMahon et al., 2019). However, it was unclear if this remained the optimal method due to changes in overall SW to a single joint task, such as the 90:90 hamstring assessment. Consistent with previous literature, F100 and F200 demonstrated improved reliability regardless of the onset threshold used (Ripley et al., 2023; Ripley et al., 2024); however, the improved reliability when using SW5SD and SW15N supports the use of the previous method identified with the isometric mid-thigh pull, SW_{5SD}. A single study has observed the effect of fatigue on RFD within the 30:30 isometric assessment (Bettariga et al., 2023), the authors did not identify the method used to identify force onset, however, due to the small to significant effects when using different onset thresholds future research should look to identify onset and to utilize SW_{5SD} method. Consistent with the present study, moderate reliability was observed for RFD by Bettargia et al. (2023), with moderate-to-large decreases in RFD identified across early time points, highlighting its utility despite the need for accurate onset identification.

Previous literature has attempted to identify optimal onset thresholds in multi-joint isometric assessments, specifically the isometric mid-thigh pull (Dos'Santos et al., 2017; Guppy et al., 2024). Dos'Santos and colleagues (2017) recommended that 5SD of SW should be used by practitioners and scientists when measures of rapid force (F100, F200) and RFD are of interest. When onset of force was identified as 5SD of SW produced the lowest time specific force values in comparison to other automated methods, this contrasts the results of the present study as the 5SD of SW method resulted in the highest onset threshold, hence identified the most significant forces at set time (F100 and F200) and RFD to 200 ms following onset in comparison to other methods. Acceptable agreement was observed between SW_{5SD}, $SD_{15N,}$ and SW_{30} for RFD, with no agreement identified for any other force measure. The agreement between onset thresholds is likely due to the lower onset force values potentially picking up unwanted artefacts within the force trace as the onset, not the true initiation of force contraction. In comparison to the isometric mid-thigh pull, agreement was observed between 2.5 and 5% SW and SW_{5SD} for time-specific force values (Dos'Santos et al., 2017), with inflated time-specific force values for SW_{10} and SW + 75N. The authors suggested this was related to the lower onset bias observed, with values identified on a lower portion of the slope of the force-time curve. This is in contrast to the present study where SW_{5SD} had the highest onset bias (i.e., greatest onset thresholds force value), to a small-large magnitude, which appears to be most useful for single joint tasks where the overall SW is considerably lower when compared to the isometric mid-thigh pull where SW accounts for the participants entire body mass. More recently, Guppy et al. (2024) performed a similar study using the isometric mid-thigh pull, comparing automated onset using SW + 40 N, SW_{5SD}, and 3SD of SW with manual identification. Automated relative thresholds (i.e., SW_{5SD} and 3SD of SW) agreed with manual identification of onset, substantial differences were observed for time-dependent measures, with no agreement with force at 50 ms and 150 ms (Guppy et al., 2024). Guppy et al. (2024) highlighted that automated thresholds were slightly more reliable in identifying time-dependent measures, which is supported by both Dos'Santos et al. (2017), where SW plus an absolute value of 75 N and SW +10% had the lowest absolute and relative reliability. However, the improved reliability of the present was related to the highest onset threshold, SW_{5SD} and SW_{15}, highlighting that the variability of the weighing period impacts time-dependent measures of force. The three percentage-based methods (SW_{10}, $SW_{20,}$ and SW_{30}) may not be sufficient to achieve an accurate identification, and due to the lower onset bias, they have increased variability; therefore, future research may consider larger percentages of SW to identify onset accurately.

It is crucial for practitioners and scientists to accurately report methods of data collection and data analysis for all assessments to aid in replication. Both Dos'Santos et al. (2017) and Guppy et al. (2024) highlight the need for consistency and accuracy of reporting when attempting to perform force plate assessments for longitudinal monitoring. Hence, standard operating procedures should be followed for all force plate assessments using evidence methodologies such as those provided for the isometric mid-thigh pull (Comfort et al., 2019; Guppy et al., 2018a, 2018b). For the single joint isometric assessments, such as the 90:90 isometric hamstring assessment and other variants, this is imperative for consistency and accuracy especially when using these methods to monitor training, injury risk and fatigue which can have implications on player selection, training, return to sport and health highlighting the necessity of developing recommendations for practitioners and scientists to follow (Bettariga et al., 2023; Constantine et al., 2019; Cuthbert et al., 2021; Matinlauri et al., 2019; McCall et al., 2015; Moreno-Perez et al., 2020; Ripley et al., 2023; Ripley et al., 2024; Taberner & Cohen, 2018).

This study is not without limitations. Firstly, onset identification has only been performed using multi-joint assessments with larger SW; the same methods could not work directly with the single joint assessments. Therefore, the methods developed and used within this study are variations of those used in multi-joint tasks and may require further refinement to ensure an optimal approach can be determined in identifying force onset during single-joint tasks. Moreover, the participants within this study were a homogeneous sample of soccer players, who may exhibit low relative shank weights, impacting the accuracy of onset as identified by the different identification methods. Future research should include a wider sample of participants, such as rugby and American footballers, in which different shank weights may be expected to be heavier. The application of the conclusions of this study to the other variants also needs further investigation, especially for the 90:20 isometric assessment where SW could be exponentially greater than in the 90:90 assessment due to the testing position testing the entire lower limb, plus the potential for inflated SW through hamstring muscle testing (Cejudo et al., 2021).

CONCLUSIONS

Practitioners and scientists who want to longitudinally assess time-dependent measures of force, such as force at set time points or RFD, in order to monitor responses from training, injury risk and fatigue need to consider the method of onset identification as there are meaningful differences observed in time-dependent measures of force when using different methods of identifying onset for the 90:90 isometric hamstring assessment. Moreover, as absolute and relative reliability were also impacted by the onset threshold method used, the greatest reliability for time-dependent force measures was observed for SW_{5SD} and SW_{15N}. As single joint isometric assessments are relatively new, with the first study published in 2015 (McCall et al., 2015), this should enable and empower practitioners and scientists to work collaboratively to develop standard operating procedures for both the collection and analysis of single joint isometric hamstring assessments when using force plates. It is recommended that all practitioners adopt a standard operating procedure for single joint isometric hamstring assessments when using force plates that ensures both reliable and accurate results. However, scientists should ensure accurate reporting of onset threshold to allow appropriate comparison.

Disclosure statement

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

Data availability

All data is available at a reasonable request to the corresponding author.

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