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Assessment of unloaded and loaded squat jump performance with a force platform: Which jump starting threshold provides more reliable outcomes?

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ABSTRACT

This study aimed to explore the influence of different onset thresholds on the between-session reliability and magnitude of squat jump (SJ) performance. Twenty men were tested on two sessions separated by 48 h against external loads of 0.5, 30 and 60 kg. The initiation of the jump was defined as the first instant in which the vertical ground reaction force exceeded system weight by 10 N (10 N), 50 N (50 N), 1% of system weight (1%SW), 10% of system weight (10%SW) and five standard deviation of system weight minus 30 ms (5SDSW). The following variables were calculated from the force-time signal collected on a force platform: mean, peak and time to peak values of force, power and velocity, average rate of force development, peak rate of force development, rate of force development index, impulse, jump height, and push-off time. The 50 N, 10%SW and 5SDSW thresholds generally revealed a higher reliability than the 10 N and 1%SW thresholds (97 and 21 out of 252 comparisons for the coefficient of variation and intra-class correlation coefficient, respectively). The magnitude of most of the variables calculated using the 50 N and 10%SW thresholds significantly differed with respect to the 10 N, 1%SW and 5SDSW thresholds ($P < 0.05$). These results suggest that both the reliability and magnitude of SJ performance variables are influenced by the jump starting threshold. The 50 N, 10%SW and 5SDSW thresholds maximise the reliability of SJ performance variables, while the 5SDSW should be recommended since it considers more force signal than the 50 N and 10%SW thresholds.

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1. Introduction

Vertical jumping is a fundamental motor skill used to evaluate the mechanical characteristics of lower-body muscles (Eagles et al., 2015). The force platform is the device most commonly used to comprehensively evaluate vertical jump performance (Cronin et al., 2004; Giroux et al., 2015). Although jump height is the main indicator of vertical jump performance, the analysis of vertical ground reaction force (VGRF) data allows users to calculate other important variables such as mean, peak and time to peak values of force, power and velocity (García-Ramos et al., 2016a; McLellan et al., 2011), rate of force development (McLellan et al., 2011), impulse (Mitchell et al., 2017), and push-off time (Anderson & Pandy, 1993). Previous studies have found appreciable differences in the reliability outcomes of the aforementioned

variables (García-Ramos et al., 2016a; McLellan et al., 2011; Moir et al., 2005). For example, the mean and peak values of force, power and velocity have shown an acceptable reliability during the squat jump (SJ) exercise (García-Ramos et al., 2016a), while the reliability of the time to peak force and rate of force development has been questioned (McLellan et al., 2011). Note that the SJ is commonly used for testing the lower-body muscle function in the field of strength and conditioning because the ability to quickly accelerate the body from a resting position is a key factor in many sporting activities (García-Ramos et al., 2016; Travis et al., 2018).

One of the methodological issues that may influence the reliability of vertical jump performance variables collected on a force platform is the procedure used to determine the onset of the movement (Meylan et al., 2011). Several jump starting thresholds have been used to analyse SJ performance suggesting a lack of agreement in the scientific literature. Researchers have used absolute jump starting thresholds such as 10 N (Moir et al., 2005), 20 N (Chandler et al., 2018) or 50 N (Giroux et al., 2015), or jump

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starting thresholds relative to the system weight such as 5% (García-Ramos et al., 2016a). To determine an appropriate time point at which velocity is likely to be zero, Owen et al. (2014) have proposed a threshold equal to 5 times the standard deviation (SD) of system weight minus 30 ms (5SDSW) for the assessment of the unloaded countermovement jump (CMJ). However, to our knowledge, the feasibility of the 5SDSW threshold for testing the SJ has not been explored yet. It also remains virtually unknown how different jump starting thresholds may influence both the reliability and magnitude of SJ performance variables.

The use of non-conservative thresholds (i.e., early detection of the initiation of the jump; e.g., 10 N [10 N] or 1% of the system weight [1%SW]) may promote the determination of the onset of the movement before it occurs, while conservative thresholds (i.e., later detection of the initiation of the jump; e.g., 50 N [50 N] 10% of the system weight [10%SW]) may exclude from the analysis the initial part of the jump. To our knowledge, only one study has examined the influence of three jump starting thresholds (2.5%SW, 5%SW and 10%SW) on the reliability and magnitude of unloaded CMJ performance variables (Meylan et al., 2011). Meylan et al. (2011) reported a comparable reliability between the jump starting thresholds for the variables collected during the concentric phase, while the most conservative threshold (i.e., 10%SW) generally provided the highest reliability for the variables collected during the eccentric phase. Therefore, the 2.5%SW threshold was recommended for assessing the concentric variables since it considers more signal for the analysis. It is reasonable that more conservative jump starting thresholds could be needed during the SJ compared to the CMJ due to the greater variability expected during the weighing phase (isometric position at 90° knee angle). This problem could be magnified when participants have to maintain a squat position isometrically with external loads on the shoulders (Pérez-Castilla et al., 2017). Therefore, since unloaded and loaded SJ exercise are increasingly used to comprehensively evaluate lower-body ballistic performance (García-Ramos et al., 2017; Samozino et al., 2014), this information could be of special importance in order to adopt a consistent threshold that allows the comparison of the magnitude of the performance variables between different research centers.

To address the gaps raised above, the present study attempted to identify the most appropriate jump starting threshold for assessing unloaded and loaded SJ performance with a force platform. Specifically, the aim of this study was to compare the reliability and magnitude of SJ performance variables between five jump starting thresholds (10 N, 50 N, 1%SW, 10%SW, and 5SDSW). We hypothesised that (I) the reliability of SJ performance variables would be higher for the two conservative (50 N and 10%SW) and 5SDSW thresholds compared to the two non-conservative thresholds (10 N and 1%SW), and (II) the magnitude of the variables using the 50 N and 10%SW thresholds would significantly differ with respect to the same variables obtained using the 10 N and 1%SW thresholds. No specific hypothesis regarding the magnitude of the variables collected using the 5SDSW threshold was formulated since it depends on the variability of the weighing phase.

2. Materials and methods

2.1. Participants

Twenty men (mean \pm SD: age = 23.4 \pm 3.3 years, body mass = 74.7 \pm 6.7 kg, body height = 1.76 \pm 0.07 m) volunteered to participate in the study. All participants were physically active sport science students with a minimum of two years of resistance training experience and were able to jump with a proper technique against the maximum tested load (75 kg or more). Participants

were instructed to avoid any strenuous physical activity over the course of the study. Participants were informed of the study procedures and signed a written informed consent form prior to initiating the study. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board (IRB approval: 687/CEIH/2018).

2.2. Design

A repeated-measures design was used to examine the influence of the jump starting threshold on the reliability and magnitude of different unloaded and loaded SJ performance variables. Following a familiarisation session, participants undertook two identical testing sessions separated by a minimum of 48 h. The SJ exercise was performed with six external loads (0.5, 17, 30, 45, 60, and 75 kg) in each session. Testing sessions were performed at the same time of the day (\pm 1 h) and under similar environmental conditions (\approx 22 °C and \approx 60% humidity).

2.3. Testing procedure

The testing sessions began with a 10-min standardised warm-up consisting of jogging, joint mobility, dynamic stretching, followed by six unloaded SJ and three SJ loaded by 17 kg. Once the warm-up was completed, participants rested for 3 min and then they performed two maximum SJ trials with external loads of 0.5, 17, 30, 45, 60 and 75 kg. The unloaded SJ was executed with a wooden barbell of 0.5 kg, while the loaded SJ was performed with a free-weight barbell of 17 kg. The external loads were applied in a randomised order, but the same order was maintained for each participant during both testing sessions. Rest periods of 3–4 min between trials of both the same and different loads were implemented to minimise fatigue. Trained spotters were always present to verbally encourage the participants throughout the test and lifting belts were used.

The SJ technique involved the participants standing on the centre of the force platform with the knees and hips fully extended, feet approximately shoulder-width apart, and the barbell resting across the back at the level of the acromion. Participants then descended in a continuous motion until reaching a self-selected depth (approximately 90° of knee flexion) and, after maintaining this static position for 1.5 s, they performed the concentric action with the instruction of jumping as high as possible (García-Ramos et al., 2017). An experienced examiner checked the knee angle at the bottom of the movement was approximately at 90° of knee flexion. If any countermovement was observed, which was carefully checked through the visual inspection of the force-time curve, the trial was repeated. The duration of eccentric and isometric phases was paced by auditory signals.

2.4. Measurement equipment and data analysis

All SJ were performed on a force platform (Dinascan/IBV, Biomechanics Institute of Valencia, Spain) that sampled the vertical ground reaction force (VGRF) data at 1000 Hz. The system weight (sum of body weight and external weight) was determined as the average VGRF over 1-s period during the held crouch position prior to the initiation of the jump (Moir et al., 2005). The start of the jump was defined as the first time instant when the VGRF exceeded the selected jump starting threshold (i.e., 10 N, 50 N, 1%SW, 10%SW, and 5SDSW) (Fig. 1), while the take-off was defined as the time instant when VGRF was below 10 N (Mundy et al., 2016). Following the recommendation of Owen et al. (2014) to determine the 5SDSW threshold, 30 ms were subtracted from the time point in which the VGRF exceeded the system weight plus 5 times the SD of the VGRF recorded during the weighing phase. Only

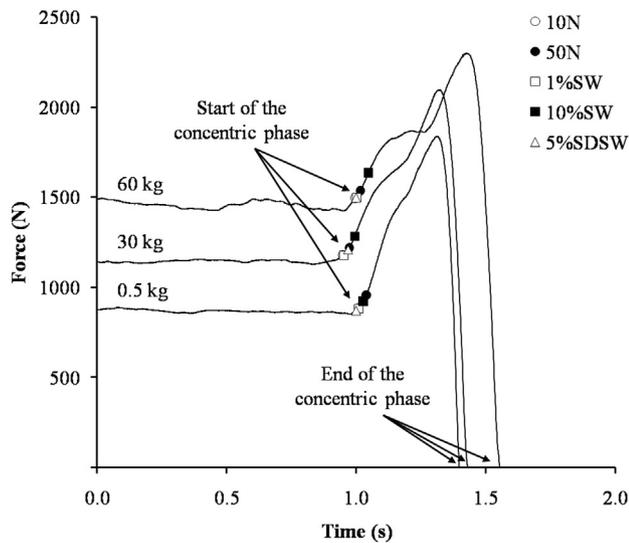


Fig. 1. Force-time curve from a representative participant (body mass = 86.5 kg) showing the five different jump starting thresholds during a SJ trial performed against an external load of 0.5, 30 and 60 kg. Note that the initiation of the concentric phase slightly differed between the jump starting thresholds, being in this example especially overlapped for the 1%SW, 10 N and 5SDSW thresholds. Note that the variability of the weighing phase increases with the increment of the external load.

the external loads of 0.5, 30 and 60 kg were used for statistical analyses to simplify the results. Specifically, the jump starting threshold value attained at 0.5, 30 and 60 kg was an increase above SW of 7.5 ± 0.7 N (range: 6.5–8.7 N), 10.3 ± 0.7 N (range: 9.3–11.5 N) and 13.8 ± 0.7 N (range: 9.3–11.5 N) for the 1%SW threshold, 74.6 ± 6.6 N (range: 65.0–86.7 N), 103.4 ± 6.6 N (range: 93.4–115.1 N) and 137.8 ± 7.0 N (range: 128.6–150.9 N) for the 10%SW threshold, and 29.8 ± 10.2 N (range: 11.7–48.7 N), 48.0 ± 19.6 N (range: 21.7–91.7 N) and 66.8 ± 31.8 N (range: 23.7–152.7 N) for the 5SDSW, respectively. The impulse-momentum approach was used to calculate the dependent variables of the present study (Linthorne, 2001). Specifically, vertical acceleration was calculated as the net VGRF divided by system weight, while vertical velocity of the centre-of-mass was determined by integrating acceleration with respect to time. The following variables were calculated to conduct a comprehensive analysis of the SJ performance:

- *Mean values:* Force, power and velocity values averaged throughout the propulsive phase of the jump (i.e., from the onset of the jump until the take-off) (García-Ramos et al., 2016a).
- *Peak values:* Maximum values of force, power and velocity achieved over the propulsive phase of the jump (Moir et al., 2005).
- *Time to peak values:* Time from the onset of the jump until reaching the maximum values of force, power and velocity (McLellan et al., 2011).
- *Rate of force development:* The average rate of force development (aRFD) was calculated as the peak force divided by the time taken to achieve the peak force (McLellan et al., 2011). The peak rate of force development (pRFD) was calculated as the highest increment between two consecutive force (i.e., time frames of 0.001 s) recordings during the propulsive phase of the jump. The rate of force development index (iRFD) was calculated as the pRFD divided by the time taken to achieve the pRFD (Boullousa et al., 2018).
- *Impulse:* Area under the force-time curve during the propulsive phase of the jump divided by body mass (Mitchell et al., 2017).

- *Jump height:* The height of the jump calculated from the take-off velocity (Pérez-Castilla et al., 2017).
- *Push-off time:* Time needed to perform the propulsive phase of the jump (Anderson & Pandy, 1993).

Only the trial with the lowest SD recorded during the 1-s averaging period for each external load was used for statistical analyses. A custom-made Microsoft Excel® spreadsheet (Microsoft Corporations, Redmond, Washington, USA) was used to calculate the variables described above.

2.5. Statistical analyses

Descriptive statistics are presented as means and SD. The normal distribution of the data was confirmed by the Shapiro-Wilk test ($P > 0.05$). Reliability was assessed by the coefficient of variation (CV) and the intraclass correlation coefficient (ICC; model 3,1) with the corresponding 95% confidence interval (CI). Acceptable reliability was determined as an $CV < 10\%$ and $ICC > 0.70$ (Cormack et al., 2008). A higher reliability of one threshold was identified when the CV was below or the ICC above the 95% CI of another threshold (García-Ramos et al., 2018). The minimal detectable change (MDC) was also calculated as $1.96 \times \sqrt{2} \times \text{standard error of measurement}$ (Thompson et al., 2008). A two-way repeated measures analysis of variance (ANOVA) (threshold [10 N, 50 N, 1%SW, 10%SW, and 5SDSW] \times load [0.5, 30, and 60 kg]) was conducted to compare the magnitude of each dependent variable. The Greenhouse-Geisser correction was used when the Mauchly's sphericity test was violated and pairwise differences were identified using Bonferroni post-hoc corrections. Eta squared (η^2) was calculated for the ANOVAs where the values of the effect sizes 0.01, 0.06, and above 0.14 were considered small, medium, and large, respectively (Cohen, 1988). Reliability analyses were performed by means of a custom spreadsheet (Hopkins, 2000), while all other statistical analyses were performed using the software package SPSS (IBM SPSS version 22.0, Chicago, IL, USA). Alpha was set at 0.05.

3. Results

3.1. Reliability of SJ variables

A total of 39 CV and ICC outcomes were calculated for each jump starting threshold (13 variables \times 3 loads). An acceptable CV value (i.e., $CV < 10\%$) was observed in 12 occasions for the 10 N, 25 for the 50 N, 16 for 1%SW, 25 for the 10%SW and 22 for the 5SDSW (Table 1). An acceptable ICC value (i.e., $ICC > 0.70$) was observed in 14 occasions for the 10 N, 24 for the 50 N, 16 for 1%SW, 22 for the 10%SW and 18 for the 5SDSW (Table 2). The reliability was generally comparable between the 50 N, 10%SW and 5SDSW thresholds (only in 9 out of 135 comparisons the CV value was significantly different, while no significant differences were observed for any ICC value). The reliability of the 50 N, 10%SW and 5SDSW thresholds was generally higher compared to the 10 N and 1%SW thresholds (97 and 21 out of 252 comparisons for the CV and ICC, respectively). The peak force and pRFD values were not compared since they did not differ between the jump starting thresholds. The MDC are depicted in Table 3.

3.2. Magnitude of SJ performance variables

The ANOVA revealed a significant main effect of 'threshold' ($F_{(4,76)} \geq 7.16$, $P \leq 0.04$, $\eta^2 \geq 0.27$) and 'load' ($F_{(2,38)} \geq 6.44$, $P \leq 0.04$, $\eta^2 \geq 0.25$) for all variables. The interaction 'threshold \times load' also reached statistical significance for all variables ($F_{(8,152)} \geq 20.0$, $P < 0.001$, $\eta^2 \geq 0.51$). The pairwise comparisons

Table 1
Coefficient of variation (CV) and 95% confidence intervals obtained for each variable separately for each jump starting threshold.

Variable	Threshold	0.5 kg	30 kg	60 kg
Mean force	10 N	5.15 (3.92, 7.53)	4.32 (3.28, 6.31)	4.17 (3.17, 6.09)
	50 N	4.30 (3.27, 6.28)	3.81 (2.90, 5.57)	2.47 (1.88, 3.61)
	1%SW	5.09 (3.87, 7.44)	4.29 (3.26, 6.26)	2.80 (2.13, 4.10)
	10%SW	4.04 (3.08, 5.59)	3.91 (2.97, 5.71)	2.55 (1.94, 3.72)
	5SDSW	4.30 (3.27, 6.28)	3.59 (2.73, 5.25)	2.36 (1.80, 3.45)
Mean power	10 N	12.0 (9.10, 17.5)	16.9 (12.8, 24.6)	18.0 (13.7, 26.3)
	50 N	9.98 (7.59, 14.6)	9.16 (6.96, 13.4) ^{a,c}	7.38 (5.61, 10.8) ^a
	1%SW	11.8 (8.95, 17.2)	12.2 (9.26, 17.8)^a	9.37 (7.13, 13.7) ^a
	10%SW	9.39 (7.14, 13.7)	8.74 (6.64, 12.8) ^{a,c}	6.97 (5.30, 10.8) ^{a,c}
	5SDSW	10.5 (8.01, 15.4)	10.1 (7.66, 14.7)^a	6.21 (4.73, 9.07) ^{a,c}
Mean velocity	10 N	9.57 (7.28, 14.0)	14.2 (10.8, 20.7)	17.3 (13.1, 25.2)
	50 N	7.33 (5.57, 10.7)	7.38 (5.61, 10.8) ^{a,c}	5.88 (4.47, 8.59) ^{a,c}
	1%SW	9.42 (7.19, 13.8)	11.1 (8.42, 16.2)	7.78 (5.91, 11.4) ^a
	10%SW	6.84 (5.20, 9.99) ^{a,c}	6.84 (5.20, 10.0) ^{a,c}	5.43 (4.13, 7.92) ^{a,c}
	5SDSW	8.20 (6.23, 12.0)	8.63 (6.56, 12.6) ^a	5.08 (3.86, 7.42) ^{a,c}
Peak force	All	2.80 (2.13, 4.08)	4.14 (3.15, 6.04)	2.20 (1.68, 3.22)
Peak power	10 N	5.04 (3.83, 7.36)	5.77 (4.39, 8.42)	5.28 (4.01, 7.71)
	50 N	5.10 (3.88, 7.45)	5.86 (4.46, 8.56)	4.87 (3.71, 7.12)
	1%SW	5.10 (3.88, 7.45)	5.81 (4.42, 8.49)	4.94 (3.76, 7.22)
	10%SW	5.20 (3.95, 7.59)	5.88 (4.48, 8.59)	4.89 (3.72, 7.14)
	5SDSW	4.96 (3.77, 7.25)	5.80 (4.41, 8.47)	5.17 (3.93, 7.55)
Peak velocity	10 N	3.09 (2.35, 4.51)	3.50 (2.66, 5.11)	4.59 (3.49, 6.71)
	50 N	3.13 (2.38, 4.56)	3.59 (2.73, 5.24)	4.10 (3.12, 6.00)
	1%SW	3.14 (2.39, 4.58)	3.55 (2.70, 5.19)	4.21 (3.20, 6.15)
	10%SW	3.19 (2.43, 4.66)	3.60 (2.74, 5.25)	4.09 (3.11, 5.98)
	5SDSW	3.05 (2.32, 4.45)	3.54 (2.69, 5.17)	4.35 (3.31, 6.35)
Time to peak force	10 N	14.7 (11.2, 21.4)	22.1 (16.8, 32.3)	33.3 (25.3, 48.6)
	50 N	10.0 (7.61, 14.6)^{a,c}	13.8 (10.5, 20.2)^a	13.5 (10.2, 19.7)^a
	1%SW	14.7 (11.2, 21.5)	17.1 (13.0, 24.9)	16.5 (12.5, 24.1)^a
	10%SW	9.36 (7.12, 13.7) ^{a,c}	13.9 (10.6, 20.4)^a	15.3 (11.7, 22.4)^a
	5SDSW	11.3 (8.60, 16.5)	12.9 (9.81, 18.8)^{a,c}	15.7 (12.0, 22.9)^a
Time to peak power	10 N	12.8 (9.74, 18.7)	19.5 (14.8, 28.5)	31.0 (23.6, 42.3)
	50 N	8.46 (6.43, 12.4) ^{a,c}	11.2 (8.53, 16.4)^a	11.7 (8.86, 17.0)^a
	1%SW	12.9 (9.80, 18.8)	14.6 (11.1, 21.3)^a	14.7 (11.2, 21.5)^a
	10%SW	7.73 (5.88, 11.3) ^{a,c}	11.0 (8.38, 16.1)^{a,c}	13.0 (9.87, 19.0)^a
	5SDSW	9.97 (7.58, 14.6)	10.6 (8.05, 15.5)^{a,c}	13.7 (10.4, 20.2)^a
Time to peak velocity	10 N	11.5 (8.71, 16.7)	17.7 (13.5, 25.9)	28.8 (21.9, 42.1)
	50 N	7.39 (5.62, 10.8) ^{a,c}	9.80 (7.46, 14.3) ^{a,c}	10.7 (8.12, 15.6)^a
	1%SW	11.5 (8.76, 16.8)	12.9 (9.84, 18.9)^a	13.5 (10.3, 19.8)^a
	10%SW	6.67 (5.08, 9.75) ^{a,c,e}	9.56 (7.27, 14.0) ^{a,c}	11.7 (8.90, 17.1)^a
	5SDSW	8.81 (6.70, 12.9)	9.37 (7.12, 13.7) ^{a,c}	12.7 (9.67, 18.6)^a
aRFD	10 N	17.6 (13.4, 25.7)	22.8 (17.3, 33.2)	29.4 (22.3, 42.9)
	50 N	14.6 (11.1, 21.3)	18.3 (13.9, 26.8)	14.5 (11.1, 21.2)^a
	1%SW	18.0 (13.7, 26.3)	21.9 (16.7, 32.0)	17.0 (12.9, 24.8)^a
	10%SW	13.5 (10.2, 19.7)	18.2 (13.9, 26.6)	16.1 (12.3, 23.6)^a
	5SDSW	13.5 (10.3, 19.8)	17.7 (13.5, 25.8)	14.0 (10.6, 20.4)^a
pRFD	All	19.7 (15.0, 28.8)	17.9 (13.6, 26.2)	23.9 (18.2, 34.9)
iRFD	10 N	81.9 (62.3, 119.6)	75.3 (57.3, 110.0)^d	97.3 (74.0, 142.1)^d
	50 N	78.6 (59.8, 114.8)	80.3 (61.1, 117.3)^d	89.1 (67.7, 130.1)^d
	1%SW	84.3 (64.1, 123.1)	69.8 (53.1, 101.9)^d	81.8 (62.2, 119.5)^d
	10%SW	79.6 (60.5, 116.3)	111.2 (84.6, 162.4)	154.5 (117.5, 225.6)
	5SDSW	55.5 (42.2, 81.0)^{a,b,c,d}	49.9 (37.9, 72.9)^{a,b,c,d}	71.2 (54.2, 104.0)^{a,d}
Impulse	10 N	5.81 (4.42, 8.49)	11.9 (9.08, 17.4)	21.5 (16.4, 31.4)
	50 N	3.38 (2.59, 4.94) ^{a,c}	5.80 (4.41, 8.47) ^{a,c}	7.22 (5.49, 10.5) ^{a,c}
	1%SW	5.96 (4.53, 8.71)	8.18 (6.22, 12.0) ^a	9.70 (7.38, 14.2) ^a
	10%SW	2.84 (2.16, 4.15) ^{a,c,e}	5.45 (4.15, 7.97) ^{a,c}	7.82 (5.95, 11.4) ^a
	5SDSW	4.31 (3.27, 6.29) ^{a,c}	5.37 (4.36, 8.37) ^{a,c}	9.24 (7.03, 13.5) ^a
Jump height	10 N	7.21 (5.48, 10.5)	10.3 (7.81, 15.0)	12.7 (9.67, 18.6)
	50 N	7.32 (5.57, 10.7)	10.9 (8.06, 15.5)	11.8 (8.96, 17.2)
	1%SW	7.32 (5.57, 10.7)	10.6 (8.03, 15.5)	11.9 (9.04, 17.4)
	10%SW	7.48 (5.69, 10.9)	10.7 (8.13, 15.6)	11.8 (8.99, 17.3)
	5SDSW	7.11 (5.40, 10.4)	10.6 (8.03, 15.4)	12.4 (9.43, 18.1)

Table 1 (continued)

Variable	Threshold	0.5 kg	30 kg	60 kg
Push-off time	10 N	10.8 (8.24, 15.8)	16.7 (12.7, 24.4)	26.5 (20.1, 38.7)
	50 N	7.11 (5.41, 10.4) ^{a,c}	9.32 (7.09, 13.6) ^a	9.84 (7.48, 14.4) ^a
	1%SW	10.9 (8.28, 15.9)	12.0 (9.15, 17.6)^a	12.6 (9.56, 18.4)^a
	10%SW	6.43 (4.89, 9.39) ^{a,c}	9.14 (6.95, 13.4) ^{a,c}	10.7 (8.12, 15.6)^a
	5SDSW	8.44 (6.42, 12.3) ^{a,c}	8.93 (6.79, 13.0) ^{a,c}	11.7 (8.88, 17.1)^a

SD, standard deviation; SW, system weight; aRFD, average rate of force development; pRFD, peak rate of force development; iRFD, rate of force development index. Bold numbers indicate an unacceptable reliability (CV > 10%). ^aSignificantly more reliable than 10 N; ^bSignificantly more reliable than 50 N; ^cSignificantly more reliable than 1%SW; ^dSignificantly more reliable than 10%SW; ^eSignificantly more reliable than 5SDSW. Meaningful differences were identified when the CV of one threshold was below the 95% confidence interval of another threshold. The peak force and pRFD values were not compared since they did not differ between the jump starting thresholds.

Table 2

Intraclass correlation coefficient (ICC) and 95% confidence intervals obtained for each variable separately for each jump starting threshold.

Variable	Threshold	0.5 kg	30 kg	60 kg
Mean force	10 N	0.73 (0.43, 0.88)	0.80 (0.56, 0.92)	0.63 (0.28, 0.84)
	50 N	0.79 (0.55, 0.91)	0.82 (0.61, 0.93)	0.86 (0.67, 0.94) ^a
	1%SW	0.76 (0.48, 0.90)	0.78 (0.52, 0.91)	0.78 (0.52, 0.91)
	10%SW	0.83 (0.61, 0.93)	0.75 (0.47, 0.89)	0.86 (0.68, 0.94) ^a
	5SDSW	0.80 (0.55, 0.91)	0.79 (0.55, 0.91)	0.86 (0.67, 0.94) ^a
Mean power	10 N	0.63 (0.27, 0.87)	0.53 (0.13, 0.79)	0.43 (0.00, 0.73)
	50 N	0.66 (0.32, 0.85)	0.74 (0.45, 0.89)	0.83 (0.61, 0.93) ^a
	1%SW	0.69 (0.36, 0.86)	0.68 (0.36, 0.86)	0.71 (0.40, 0.87)
	10%SW	0.69 (0.37, 0.87)	0.75 (0.47, 0.89)	0.83 (0.62, 0.93) ^a
	5SDSW	0.66 (0.31, 0.85)	0.71 (0.40, 0.87)	0.88 (0.71, 0.95) ^{a,b}
Mean velocity	10 N	0.61 (0.24, 0.73)	0.51 (0.10, 0.77)	0.33 (-0.11, 0.67)
	50 N	0.64 (0.29, 0.84)	0.66 (0.32, 0.85)	0.82 (0.59, 0.92) ^a
	1%SW	0.69 (0.37, 0.87)	0.59 (0.21, 0.81)	0.72 (0.42, 0.88) ^a
	10%SW	0.66 (0.32, 0.85)	0.67 (0.33, 0.85)	0.81 (0.57, 0.92) ^a
	5SDSW	0.62 (0.26, 0.83)	0.61 (0.25, 0.83)	0.87 (0.70, 0.95) ^a
Peak force	All	0.94 (0.85, 0.98)	0.85 (0.67, 0.94)	0.93 (0.83, 0.97)
Peak power	10 N	0.89 (0.74, 0.95)	0.86 (0.69, 0.94)	0.89 (0.75, 0.96)
	50 N	0.89 (0.74, 0.95)	0.86 (0.68, 0.94)	0.91 (0.78, 0.96)
	1%SW	0.88 (0.73, 0.95)	0.86 (0.68, 0.94)	0.91 (0.78, 0.96)
	10%SW	0.88 (0.73, 0.95)	0.86 (0.68, 0.94)	0.92 (0.80, 0.97)
	5SDSW	0.89 (0.74, 0.96)	0.86 (0.69, 0.94)	0.90 (0.76, 0.96)
Peak velocity	10 N	0.88 (0.73, 0.95)	0.86 (0.68, 0.94)	0.84 (0.64, 0.93)
	50 N	0.88 (0.73, 0.95)	0.86 (0.67, 0.94)	0.87 (0.71, 0.95)
	1%SW	0.88 (0.72, 0.95)	0.86 (0.67, 0.94)	0.87 (0.70, 0.95)
	10%SW	0.88 (0.73, 0.95)	0.86 (0.68, 0.94)	0.89 (0.75, 0.96)
	5SDSW	0.89 (0.73, 0.95)	0.86 (0.67, 0.94)	0.86 (0.68, 0.94)
Time to peak force	10 N	0.55 (0.15, 0.79)	0.66 (0.32, 0.85)^{b,c}	0.29 (-0.16, 0.64)
	50 N	0.76 (0.50, 0.90)	0.48 (0.06, 0.75)	0.66 (0.32, 0.85)^a
	1%SW	0.65 (0.31, 0.85)	0.23 (-0.22, 0.60)	0.55 (0.15, 0.79)
	10%SW	0.79 (0.54, 0.91)	0.52 (0.11, 0.58)	0.63 (0.27, 0.84)
	5SDSW	0.61 (0.25, 0.83)	0.46 (0.04, 0.75)	0.53 (0.13, 0.79)
Time to peak power	10 N	0.51 (0.10, 0.77)	0.69 (0.36, 0.86)^b	0.27 (-0.19, 0.63)
	50 N	0.73 (0.43, 0.88)	0.44 (0.01, 0.73)	0.64 (0.29, 0.84)^a
	1%SW	0.63 (0.27, 0.83)	0.21 (-0.24, 0.59)	0.52 (0.11, 0.78)
	10%SW	0.75 (0.48, 0.89)	0.49 (0.08, 0.76)	0.62 (0.25, 0.83)
	5SDSW	0.55 (0.16, 0.80)	0.43 (0.00, 0.73)	0.51 (0.10, 0.77)
Time to peak velocity	10 N	0.52 (0.11, 0.78)	0.68 (0.36, 0.86)^b	0.26 (-0.19, 0.62)
	50 N	0.74 (0.45, 0.89)	0.45 (0.02, 0.74)	0.63 (0.28, 0.84)^a
	1%SW	0.64 (0.28, 0.84)	0.22 (-0.23, 0.60)	0.51 (0.10, 0.77)
	10%SW	0.77 (0.50, 0.90)	0.49 (0.08, 0.76)	0.61 (0.24, 0.83)
	5SDSW	0.57 (0.19, 0.81)	0.45 (0.02, 0.74)	0.49 (0.08, 0.76)
aRFD	10 N	0.71 (0.40, 0.88)	0.48 (0.06, 0.76)	0.28 (-0.18, 0.63)
	50 N	0.80 (0.56, 0.92)	0.48 (0.06, 0.76)	0.70 (0.39, 0.87) ^a
	1%SW	0.73 (0.43, 0.88)	0.29 (-0.17, 0.64)	0.63 (0.27, 0.84)
	10%SW	0.83 (0.62, 0.93)	0.52 (0.12, 0.78)	0.68 (0.36, 0.86)^a
	5SDSW	0.77 (0.50, 0.90)	0.48 (0.06, 0.75)	0.70 (0.38, 0.87) ^a
pRFD	All	0.66 (0.32, 0.85)	0.59 (0.21, 0.81)	0.10 (0.35, 0.51)
iRFD	10 N	0.22 (-0.24, 0.59)	0.60 (0.23, 0.82)	-0.18 (-0.57, 0.27)
	50 N	0.24 (-0.22, 0.61)	0.52 (0.11, 0.78)	0.05 (-0.39, 0.47)
	1%SW	0.25 (-0.21, 0.61)	0.62 (0.25, 0.83)	0.05 (-0.39, 0.47)
	10%SW	0.26 (-0.20, 0.62)	0.37 (-0.08, 0.69)	-0.15 (-0.55, 0.30)
	5SDSW	0.32 (-0.13, 0.66)	0.54 (0.14, 0.79)	-0.04 (-0.47, 0.40)

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Table 2 (continued)

Variable	Threshold	0.5 kg	30 kg	60 kg
Impulse	10 N	0.86 (0.69, 0.94)	0.70 (0.38, 0.87)	0.31 (-0.14, 0.65)
	50 N	0.95 (0.88, 0.98) ^a	0.73 (0.43, 0.88)	0.74 (0.46, 0.89) ^a
	1%SW	0.87 (0.71, 0.95)	0.49 (0.08, 0.76)	0.67 (0.33, 0.86)^a
	10%SW	0.96 (0.90, 0.98) ^a	0.75 (0.47, 0.89)	0.68 (0.35, 0.86)^a
	5SDSW	0.91 (0.79, 0.96)	0.74 (0.44, 0.89)	0.60 (0.23, 0.82)
Jump height	10 N	0.87 (0.71, 0.95)	0.80 (0.56, 0.92)	0.85 (0.67, 0.94)
	50 N	0.87 (0.70, 0.95)	0.85 (0.67, 0.94)	0.88 (0.72, 0.95)
	1%SW	0.87 (0.70, 0.95)	0.79 (0.54, 0.91)	0.88 (0.71, 0.95)
	10%SW	0.87 (0.70, 0.95)	0.79 (0.55, 0.91)	0.89 (0.75, 0.96)
	5SDSW	0.87 (0.71, 0.95)	0.79 (0.54, 0.91)	0.87 (0.69, 0.94)
Push-off time	10 N	0.53 (0.13, 0.78)	0.67 (0.34, 0.86)^b	0.26 (-0.19, 0.62)
	50 N	0.74 (0.44, 0.89)	0.41 (-0.02, 0.72)	0.63 (0.27, 0.83)^a
	1%SW	0.65 (0.30, 0.84)	0.22 (-0.24, 0.59)	0.52 (0.11, 0.78)
	10%SW	0.76 (0.49, 0.90)	0.44 (0.01, 0.73)	0.58 (0.20, 0.81)
	5SDSW	0.58 (0.20, 0.81)	0.42 (-0.02, 0.72)	0.49 (0.08, 0.76)

SD, standard deviation; SW, system weight; aRFD, average rate of force development; pRFD, peak rate of force development; iRFD, rate of force development index. Bold numbers indicate an unacceptable reliability (ICC > 0.70). ^aSignificantly more reliable than 10 N; ^bSignificantly more reliable than 1%SW; ^cSignificantly more reliable than 10% SW. Meaningful differences were identified when the ICC of one threshold was above the 95% confidence interval of another threshold. The peak force and pRFD values were not compared since they did not differ between the jump starting thresholds.

Table 3

Minimal detectable change (MDC) obtained for each variable separately for each jump starting threshold.

Variable	Threshold	0.5 kg	30 kg	60 kg
Mean force (N)	10 N	179.5	173.8	194.8
	50 N	153.8	159.1	119.0
	1%SW	176.2	174.8	132.7
	10%SW	146.1	165.6	124.6
	5SDSW	146.7	146.8	112.7
Mean power (W)	10 N	455.6	604.2	527.0
	50 N	403.4	358.0	251.5
	1%SW	440.8	442.5	293.7
	10%SW	387.5	351.8	250.8
	5SDSW	380.9	359.1	527.0
Mean velocity (m·s ⁻¹)	10 N	0.275	0.361	0.294
	50 N	0.224	0.205	0.117
	1%SW	0.267	0.285	0.222
	10%SW	0.213	0.195	0.114
	5SDSW	0.224	0.218	0.096
Peak force (N)	All	136.9	324.6	139.1
Peak power (W)	10 N	498.8	554.9	471.3
	50 N	502.9	560.5	430.2
	1%SW	504.7	558.2	439.6
	10%SW	510.4	557.8	423.1
	5SDSW	490.3	556.6	458.2
Peak velocity (m·s ⁻¹)	10 N	0.210	0.198	0.207
	50 N	0.212	0.201	0.183
	1%SW	0.213	0.200	0.189
	10%SW	0.216	0.200	0.179
	5SDSW	0.207	0.199	0.195
Time to peak force (s)	10 N	0.104	0.231	0.475
	50 N	0.064	0.115	0.144
	1%SW	0.108	0.160	0.202
	10%SW	0.058	0.108	0.143
	5SDSW	0.085	0.119	0.181
Time to peak power (s)	10 N	0.103	0.223	0.473
	50 N	0.062	0.104	0.136
	1%SW	0.106	0.151	0.195
	10%SW	0.054	0.096	0.134
	5SDSW	0.085	0.108	0.171
Time to peak velocity (s)	10 N	0.104	0.223	0.473
	50 N	0.062	0.103	0.137
	1%SW	0.108	0.149	0.195
	10%SW	0.054	0.094	0.135
	5SDSW	0.084	0.106	0.174

Table 3 (continued)

Variable	Threshold	0.5 kg	30 kg	60 kg
aRFD (kN·s ⁻¹)	10 N	3.57	3.69	4.07
	50 N	3.25	3.54	2.51
	1%SW	3.56	3.77	2.57
	10%SW	3.13	3.83	3.22
	5SDSW	2.54	3.08	2.23
pRFD (kN·s ⁻¹)	All	5.58	4.46	5.95
iRFD (kN·s ⁻²)	10 N	303.99	154.02	97.23
	50 N	383.83	238.67	130.12
	1%SW	299.28	149.55	89.60
	10%SW	449.63	507.42	375.71
	5SDSW	152.91	94.58	78.18
Impulse (N·s)	10 N	71.3	232.3	642.8
	50 N	39.7	99.9	179.7
	1%SW	74.2	149.7	263.5
	10%SW	32.7	90.1	179.1
	5SDSW	54.2	104.0	241.2
Jump height (m)	10 N	0.055	0.049	0.032
	50 N	0.055	0.050	0.029
	1%SW	0.056	0.050	0.030
	10%SW	0.056	0.050	0.028
	5SDSW	0.054	0.050	0.031
Push-off time (s)	10 N	0.106	0.227	0.475
	50 N	0.065	0.107	0.141
	1%SW	0.109	0.150	0.200
	10%SW	0.057	0.099	0.139
	5SDSW	0.086	0.110	0.177

SD, standard deviation; SW, system weight; aRFD, average rate of force development; pRFD, peak rate of force development; iRFD, rate of force development index. The peak force and pRFD values were not separately presented since they did not differ between the jump starting thresholds.

Table 4

Magnitude of SJ variables using different jump starting thresholds.

Variable	Threshold	0.5 kg	30 kg	60 kg
Mean force (kN)	10 N	1.25 ± 0.11 ^e	1.44 ± 0.14	1.67 ± 0.13
	50 N	1.28 ± 0.12 ^{a,c,e}	1.49 ± 0.12 ^{a,c,e}	1.73 ± 0.12 ^{a,c,e}
	1%SW	1.25 ± 0.12 ^e	1.46 ± 0.12	1.71 ± 0.11
	10%SW	1.29 ± 0.12 ^{a,b,c,e}	1.51 ± 0.13 ^{a,b,c,e}	1.76 ± 0.12 ^{a,b,c,e}
	5SDSW	1.23 ± 0.11	1.46 ± 0.11	1.72 ± 0.11 ^a
Mean power (kW)	10 N	1.38 ± 0.22 ^e	1.21 ± 0.33	1.02 ± 0.30
	50 N	1.45 ± 0.23 ^{a,c,e}	1.36 ± 0.23 ^{c,e}	1.21 ± 0.23 ^{a,c,e}
	1%SW	1.36 ± 0.24	1.28 ± 0.24	1.14 ± 0.22
	10%SW	1.48 ± 0.24 ^{a,b,c,e}	1.41 ± 0.24 ^{b,c,e}	1.27 ± 0.23 ^{a,b,c,e}
	5SDSW	1.30 ± 0.20	1.27 ± 0.21	1.17 ± 0.21
Mean velocity (m·s ⁻¹)	10 N	1.049 ± 0.123 ^e	0.806 ± 0.184	0.599 ± 0.158
	50 N	1.106 ± 0.120 ^{a,c,e}	0.902 ± 0.101 ^{a,c,e}	0.710 ± 0.103 ^{a,c,e}
	1%SW	1.035 ± 0.140 ^e	0.849 ± 0.110	0.670 ± 0.107
	10%SW	1.126 ± 0.122 ^{a,b,c,e}	0.936 ± 0.102 ^{a,b,c,e}	0.746 ± 0.098 ^{a,b,c,e}
	5SDSW	0.995 ± 0.104	0.845 ± 0.091	0.683 ± 0.093 ^a
Peak force (kN)	All	1.79 ± 0.19	2.03 ± 0.20	2.28 ± 0.18
Peak power (kW)	10 N	3.54 ± 0.50 ^{b,d}	3.44 ± 0.52 ^d	3.16 ± 0.50 ^{b,d}
	50 N	3.53 ± 0.50 ^d	3.42 ± 0.53 ^d	3.12 ± 0.51 ^d
	1%SW	3.54 ± 0.50 ^{a,b,d}	3.44 ± 0.52 ^{b,d}	3.14 ± 0.51 ^{b,d}
	10%SW	3.52 ± 0.49	3.39 ± 0.53	3.06 ± 0.52
	5SDSW	3.54 ± 0.50 ^{b,d}	3.43 ± 0.53 ^{b,d}	3.13 ± 0.51 ^{b,d}
Peak velocity (m·s ⁻¹)	10 N	2.454 ± 0.202 ^{b,d}	2.033 ± 0.185 ^d	1.601 ± 0.182 ^{b,d}
	50 N	2.446 ± 0.203 ^d	2.019 ± 0.186 ^d	1.583 ± 0.187 ^d
	1%SW	2.454 ± 0.202 ^{a,b,d}	2.028 ± 0.185 ^{b,d}	1.593 ± 0.185 ^{b,d}
	10%SW	2.440 ± 0.203	2.003 ± 0.188	1.553 ± 0.199
	5SDSW	2.452 ± 0.201 ^{b,d}	2.026 ± 0.185 ^{b,d}	1.587 ± 0.188 ^d
Time to peak force (s)	10 N	0.256 ± 0.055 ^{b,d}	0.405 ± 0.171	0.545 ± 0.231 ^{b,d}
	50 N	0.235 ± 0.051 ^d	0.314 ± 0.066 ^d	0.389 ± 0.100 ^d
	1%SW	0.263 ± 0.064 ^{b,d}	0.347 ± 0.074 ^{b,d}	0.430 ± 0.109 ^{b,d}
	10%SW	0.227 ± 0.050	0.291 ± 0.064	0.340 ± 0.096
	5SDSW	0.273 ± 0.050 ^{a,b,d}	0.346 ± 0.069 ^{b,d}	0.409 ± 0.095 ^{b,d}

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Table 4 (continued)

Variable	Threshold	0.5 kg	30 kg	60 kg
Time to peak power (s)	10 N	0.288 ± 0.049 ^{b,d}	0.439 ± 0.170 ^d	0.579 ± 0.227 ^{b,d}
	50 N	0.267 ± 0.045	0.348 ± 0.059 ^d	0.423 ± 0.094 ^d
	1%SW	0.295 ± 0.058 ^{b,d}	0.382 ± 0.068 ^{b,d}	0.464 ± 0.103 ^{b,d}
	10%SW	0.259 ± 0.043 ^b	0.326 ± 0.056	0.375 ± 0.090
	5SDSW	0.305 ± 0.044 ^{a,b,d}	0.381 ± 0.061 ^{b,d}	0.443 ± 0.088 ^{b,d}
Time to peak velocity (s)	10 N	0.328 ± 0.050 ^{b,d}	0.481 ± 0.170	0.622 ± 0.226 ^{b,d}
	50 N	0.307 ± 0.046 ^d	0.390 ± 0.058 ^d	0.465 ± 0.093 ^d
	1%SW	0.335 ± 0.060 ^{b,d}	0.423 ± 0.069 ^{b,d}	0.507 ± 0.102 ^{b,d}
	10%SW	0.299 ± 0.045	0.367 ± 0.056	0.417 ± 0.089
	5SDSW	0.345 ± 0.044 ^{a,b,d}	0.422 ± 0.061 ^{b,d}	0.486 ± 0.088 ^{b,d}
aRFD (kN·s ⁻¹)	10 N	7.32 ± 2.65 ^e	5.61 ± 2.16	4.87 ± 1.91
	50 N	7.99 ± 2.91 ^{a,c,e}	6.71 ± 1.98 ^{a,c,e}	6.28 ± 1.82 ^{a,c,e}
	1%SW	7.19 ± 2.68	6.09 ± 1.93	5.65 ± 1.60
	10%SW	8.25 ± 3.00 ^{a,b,c,e}	7.26 ± 2.20 ^{a,b,c,e}	7.22 ± 2.10 ^{a,b,c,e}
	5SDSW	6.73 ± 2.04	6.05 ± 1.75	5.88 ± 1.51 ^a
pRFD (kN·s ⁻¹)	All	10.73 ± 3.04	9.37 ± 2.70	8.94 ± 2.49
iRFD (kN·s ⁻²)	10 N	121.85 ± 89.46 ^e	62.83 ± 53.80	34.96 ± 32.96
	50 N	160.60 ± 113.70 ^{a,c,e}	89.95 ± 68.21 ^{a,c,e}	50.37 ± 42.89 ^{a,c,e}
	1%SW	117.90 ± 88.40	67.21 ± 52.58	40.34 ± 32.51
	10%SW	186.11 ± 131.15 ^{a,b,c,e}	129.95 ± 111.42 ^{a,b,c,e}	102.00 ± 152.26 ^{a,b,c,e}
	5SDSW	94.00 ± 56.31	61.70 ± 37.94	39.10 ± 25.02
Impulse (N·s)	10 N	441.6 ± 64.4 ^{b,d}	729.0 ± 179.0	1113.9 ± 302.8 ^{b,d}
	50 N	424.9 ± 58.7 ^d	632.9 ± 72.9 ^d	897.5 ± 135.3 ^d
	1%SW	447.0 ± 69.2 ^{b,d}	668.5 ± 80.5 ^{b,d}	957.4 ± 156.6 ^{b,d}
	10%SW	418.7 ± 56.1	607.7 ± 68.9	825.1 ± 121.6
	5SDSW	454.0 ± 60.2 ^{a,b,d}	667.6 ± 79.2 ^{b,d}	926.2 ± 127.1 ^{b,d}
Jump height (m)	10 N	0.274 ± 0.050 ^{b,d}	0.172 ± 0.038 ^d	0.087 ± 0.030 ^{b,d}
	50 N	0.272 ± 0.050 ^d	0.169 ± 0.038 ^d	0.085 ± 0.030 ^d
	1%SW	0.274 ± 0.050 ^{a,b,d}	0.171 ± 0.038 ^{b,d}	0.086 ± 0.030 ^{b,d}
	10%SW	0.271 ± 0.050 ^b	0.167 ± 0.038	0.082 ± 0.031
	5SDSW	0.274 ± 0.050 ^{b,d}	0.171 ± 0.038 ^{b,d}	0.086 ± 0.030 ^d
Push-off time (s)	10 N	0.353 ± 0.052 ^{b,d}	0.517 ± 0.170	0.676 ± 0.227 ^{b,d}
	50 N	0.332 ± 0.047 ^d	0.426 ± 0.059 ^d	0.520 ± 0.095 ^d
	1%SW	0.360 ± 0.062 ^{b,d}	0.459 ± 0.069 ^{b,d}	0.561 ± 0.106 ^{b,d}
	10%SW	0.324 ± 0.046	0.403 ± 0.056	0.471 ± 0.089
	5SDSW	0.370 ± 0.046 ^{a,b,d}	0.458 ± 0.062 ^{b,d}	0.540 ± 0.090 ^{b,d}

SD, standard deviation; SW, system weight; aRFD, average rate of force development; peak rate of force development; iRFD, rate of force development index. ^aSignificantly higher than 10 N; ^bSignificantly higher than 50 N; ^cSignificantly higher than 1%SW; ^dSignificantly higher than 10%SW; ^eSignificantly higher than 5%SDSW ($P < 0.05$; ANOVA with Bonferroni correction). The peak force and pRFD values were not compared since they did not differ between the jump starting thresholds.

are depicted in Table 4. The peak force and pRFD values were not compared since they did not differ between the jump starting thresholds.

4. Discussion

This study was designed to explore the influence of the jump starting threshold on the reliability and magnitude of different unloaded and loaded SJ performance variables collected with a force platform. Supporting our first hypothesis, the reliability was higher for the two conservative (50 N and 10%SW) and 5SDSW thresholds compared to the two non-conservative thresholds (10 N and 1%SW). Meaningful differences in reliability were observed for all variables with the exception of the peak values and jump height. Our second hypothesis was also confirmed since the magnitude of the different SJ performance variables obtained by the 50 N and 10%SW thresholds significantly differed with respect to 10 N and 1%SW thresholds (except peak force and pRFD). The magnitude of the variables using the 5SDSW threshold was comparable to the non-conservative thresholds. These results suggest that both the reliability and magnitude of unloaded and loaded SJ performance variables may be influenced by the jump starting threshold. The 5SDSW threshold should be recommended to maximise the reliability of SJ performance variables, while preserving more force signal than the 50 N and 10%SW thresholds.

The present study aimed to comprehensively examine the reliability of relevant kinetic and kinematic variables collected with a force platform during the unloaded and loaded SJ. Regardless of the jump starting threshold, the peak values of force, power, and velocity were the only variables that reported an acceptable reliability at all loading conditions (CV < 10% and ICC > 0.70). These findings are in agreement with previous studies that have shown a very high reproducibility of peak force (CV < 2.8% and ICC > 0.96), peak velocity (CV < 2.4% and ICC > 0.98), and peak power (CV < 4.2% and ICC > 0.94) during the SJ exercise against a range of external loads (García-Ramos et al., 2016a; McLellan et al., 2011; Moir et al., 2005). The reliability of the remaining variables was generally lower. The time to peak values, mean values, impulse and push-off time were the variables more affected by the jump starting threshold. Specifically, non-conservative thresholds (i.e., 10 N and 1%SW) should be discouraged to obtain reproducible measurements of these variables during the SJ exercise. Similar reliability findings have been reported for the time to peak force (CV = 13.2% and ICC = 0.88), aRFD (CV range = 4.6–16.9% and ICC range = 0.75–0.89) and pRFD (CV range = 12.7–17.1% and ICC range = 0.53–0.89) when a 10 N threshold was used to determine the onset of the movement during the SJ exercise (McLellan et al., 2011; Moir et al., 2005). The higher reliability observed in the present study for the peak values, which was not affected by the jump starting threshold, corroborates that peak values should

be preferably used to evaluate SJ performance (Dugan et al., 2004; García-Ramos et al., 2016a; Hori et al., 2007). Peak velocity could be specifically recommended because it is the most sensitive indicator to discriminate jumping ability (Jiménez-Reyes et al., 2016) and may present a higher association with sports performance (García-Ramos et al., 2016b).

Since it is reasonable to expect a considerable variability in the weighing phase due to the need to maintain an isometric position at 90° knee angle, we hypothesised that the reliability of the two conservative (50 N and 10%SW) and 5SDSW thresholds would be higher compared to the two non-conservative thresholds (10 N and 1%SW). Supporting our first hypothesis, meaningful differences in reliability were observed for all variables with the exception of the peak values and jump height. Meylan et al. (2015) did not find differences in reliability for the variables collected during the concentric phase during the unloaded CMJ between three jump starting thresholds (2.5%SW, 5%SW, and 10%SW). This apparent contradictory result may be explained because the criteria used for determining the start of the concentric phase during the CMJ (i.e., when velocity became positive) is practically unaffected by the jump starting threshold. It should also be noted that the variability of the weighing phase during the SJ is expected to be higher than during the CMJ due to the different positions adopted during the weighing phase (i.e., isometric 90° knee angle in SJ vs. upright position in CMJ). Therefore, it is reasonable to use more conservative jump starting threshold for analysing the SJ compared to the CMJ.

It has been argued that the variability of the force-time signal during the weighing phase should be minimised to facilitate the identification of the onset of the movement (Chavda et al., 2018; McMahon et al., 2018; Owen et al., 2014). Since non-conservative thresholds may prematurely detect the initiation of the jump and conservative thresholds may exclude the initial part of the jump from the analysis, we hypothesised that the magnitude of the variables would significantly differ between non-conservative and conservative thresholds. This hypothesis was confirmed since the magnitude of the different SJ variables generally differed between the 50 N and 10%SW compared to the 10 N and 1%SW thresholds. These findings are in line with the findings of Meylan et al. (2015) who found significant differences in all variables (except for peak force and force at zero velocity) between 2.5%SW, 5%SW and 10%SW thresholds. More importantly, the magnitude of the variables for the 5SDSW threshold was comparable to the non-conservative thresholds and significantly differed with respect to the conservative thresholds. Therefore, since it is important to adopt a consistent threshold for comparative purposes (Chavda et al., 2018), the 5SDSW threshold could be recommended to assess unloaded and loaded SJ performance performed at approximately 90° of knee flexion because it retains more force signal for the analysis in comparison with the two conservative thresholds, while it provides a comparable reliability. However, it should be noted that the 5SDSW threshold seems to be affected by the loading condition since the SD of the weighing phase is accentuated with higher external loads and, consequently, a large initial part of the jump could be excluded from the analysis when jumping against external loads.

The main limitation of the present study was the use a relatively small sample size composed exclusively of men with a variety of training backgrounds. Since it has been previously observed differences in the lower-body maximal strength and jumping ability between sexes (Beckham et al., 2019), the fact of just examining men may be a potential confounding factor. It should be noted that the variability expected during the weighing phase could be less accentuated with more skilled participants (i.e., high-level athletes) (Pérez-Castilla et al., 2017). In addition, since the starting position was not strictly standardised at 90° of knee flexion, it is

possible that the variability of the weighing phase is also affected by the initial knee angle. Future studies should explore whether sex and training background may influence the reliability and magnitude of SJ performance variables obtained from different absolute and relative jump starting thresholds. Future studies should also investigate whether similar findings are obtained in other vertical jump types (e.g. CMJ) commonly used for testing the lower-body ballistic performance.

In conclusion, the threshold used to detect the initiation of the jump influences both the reliability and magnitude of SJ performance variables. The 50 N, 10%SW and 5SDSW thresholds reported a higher reliability for several variables compared to the 10 N and 1%SW thresholds (mean and time to peak values of force, power and velocity, peak values of power and velocity, aRFD, iRFD, impulse and push-off time), but no significant differences in reliability were observed for other variables (peak values, jump height, and pRFD). The magnitude of the variables obtained by the 50 N and 10%SW thresholds generally differed with respect to the 10 N, 1%SW and 5SDSW thresholds. Therefore, in order to standardise the routine testing of SJ performance with a force platform, we recommend the 5SDSW threshold since it provides a comparable reliability than conservative thresholds (i.e., 50 N and 5%SW) but considering more force signal for the analysis.

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Conflict of interest statement

The authors declare that they have no conflict of interests.

Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jbiomech.2019.05.022>.

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