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Reliability, variability, and minimal detectable change of bilateral and unilateral lower extremity isometric force tests

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ABSTRACT

This study aimed to investigate the within- and between-session reliability, variability, and minimal detectable change (MDC) of vertical ground reaction force (vGRF) during bilateral and unilateral lower extremity maximal isometric force tests. Eighteen participants (men: n = 9, age: 27.9 ± 6.3 y, height: 1.82 ± 0.06 m, mass: 82.4 ± 10.4 kg, strength training experience: 10.4 ± 7.7 y; women: n = 9, age: 29.3 ± 8.6 y, height: 1.68 ± 0.01 m, mass: 58.0 ± 5.8 kg, strength training experience: 5.5 ± 3.6 y) attended two data collection sessions separated by 48 h. The absolute, net, and relative vGRF were calculated across bilateral and unilateral variations of the squat, standing plantarflexion, and seated plantarflexion positions. All measures of vGRF demonstrated excellent reliability and low variability within (intraclass correlation coefficients (ICC): 0.92–0.99; coefficient of variation (CV): 2.9–6.5%) and between sessions (ICC: 0.95–1.00; CV: 2.0–6.0%), across all positions. The MDC ranged between 135–276 N (5.1–14.5%), with the seated plantarflexion positions demonstrating the highest values as a percentage of the group mean (13.3–14.5%). Maximal isometric force testing during bilateral and unilateral variations of the squat, standing plantarflexion, and seated plantarflexion positions provides reliable measurement of vGRF in men and women.

1. Introduction

Maximal isometric force testing is a common method used to measure lower extremity strength. Research investigating the reliability of maximal isometric force tests has largely been conducted on the isometric mid-thigh pull using a force platform and general isometric rig (Brady et al., 2020). The isometric squat and seated and standing ankle plantarflexion have been reported in the literature, however, these investigations have used highly specialized equipment such as hack squat machines (Blazevich & Gill, 2006; Palmer et al., 2018), wall-mounted force platforms (Beckman et al., 2014), or bespoke seated force transducers (Pääsuke et al., 2000). Specialized equipment for these tests may offer limited utility in applied environments due to cost and space restrictions. Conversely, the ability to test across various positions using a force platform and general isometric rig offers science and

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medicine practitioners a practical approach to isometric force testing.

Whilst bilateral variations of maximal isometric force tests have been the most common positions investigated when establishing the reliability of lower extremity strength characteristics (Brady et al., 2020), there is increasing interest in unilateral variations (Bishop et al., 2019, 2021; Goodwin & Bull, 2021). Unilateral variations of maximal isometric force tests offer insights into the strength characteristics of the limb and inter-limb asymmetries thereof (Bishop et al., 2019). Inter-limb asymmetries are particularly valuable when developing criteria-led return-to-sport protocols following unilateral injury (Rohman et al., 2015), or when directing the emphasis of training in non-injured individuals (Bishop et al., 2021). A combination of bilateral and unilateral strength characteristics and asymmetries can also be used to inform programming decisions relating to exercise selection (Cohen et al., 2020; Stern et al., 2020). Limited research, however, has investigated the effect of both bilateral and unilateral stance on the reliability of strength characteristics during various isometric force tests (Blazevich & Gill, 2006).

The within-session reliability and variability of isometric force tests are well documented, with peak vertical ground reaction force (vGRF) demonstrating the greatest intraclass correlation coefficients (ICC) and smallest coefficients of variation (CV) compared with other variables (e.g., rate of force development) (Brady et al., 2020). The between-session reliability and variability of peak vGRF during isometric force testing, however, are less well documented (Brady et al., 2020). In addition to characterizing reliability, between-session ICCs can be used to calculate the minimal detectable change (MDC). The MDC has been used to establish thresholds for outcome variables, such as vGRF, enabling practitioners to differentiate signal from noise and identify a meaningful change (Howarth et al., 2021). No studies, however, have determined the MDC during the unilateral squat or bilateral or unilateral ankle plantarflexion variations of maximal isometric force tests (Brady et al., 2020). Data pertaining to the reliability, variability, and MDC in these positions would provide a basis for applied practitioners to use such methods to monitor neuromuscular changes specific to these positions and muscle groups.

This study aimed to investigate the within- and between-session reliability, variability, and MDC of vGRF measures during maximal isometric force tests across bilateral and unilateral variations of the squat, standing plantarflexion, and seated plantarflexion positions.

2. Methods

2.1. Study Design

A within-subject test-retest design was employed to investigate the reliability, variability, and MDC of vGRF during the isometric squat, standing plantarflexion, and seated plantarflexion tests. Two or more replicants were required to calculate ICCs ($\alpha = 0.05$, $\beta = 0.80$) based on a minimal acceptable reliability (ρ_0) of ≥ 0.7 (Koo & Li, 2016) and expected reliability (ρ_1) of ≥ 0.9 (Brady et al., 2020). The expected reliability of ≥ 0.9 was based on previous research demonstrating excellent reliability for measures of vGRF (Brady et al., 2020). *A priori* power analyses indicated that minimum samples of eighteen participants were required to calculate the ICC ($\alpha = 0.05$, $\beta = 0.80$), based on two trials recorded per participant (Walter et al., 1998), a ρ_0 of ≥ 0.7 (Walter et al., 1998), and a ρ_1 of ≥ 0.9 (Brady et al., 2020). Internal training load was calculated for the 48h preceding testing to account for differences in training load prior to testing sessions. Internal training load was calculated using the session rating of perceived exertion method for each participant, where rating of perceived exertion using the Borg CR-10 was multiplied by session duration in minutes (Shaw et al., 2020). The time of day was standardized for each participant to account for variations in circadian rhythm (Teo et al., 2011).

2.2. Participants

Nineteen participants volunteered for this research, of which eight were professional ballet dancers (men: $n = 4$; women: $n = 4$) and eleven physically active men ($n = 6$) and women ($n = 5$). One participant withdrew following the first testing session resulting in eighteen participants (men: $n = 9$, age: 27.9 ± 6.3 y, height: 1.82 ± 0.06 m, mass: 82.4 ± 10.4 kg, strength training experience: 10.4 ± 7.7 y; women: $n = 9$, age: 29.3 ± 8.6 y, height: 1.68 ± 0.01 m, mass: 58.0 ± 5.8 kg, strength training experience: 5.5 ± 3.6 y). Participants were required to have not sustained an injury in the six weeks prior to data collection. Written informed consent was gained from all participants and ethical approval was provided by the local Ethics Committee in accordance with the Declaration of Helsinki.

2.3. Procedure

All participants attended two identical data collection sessions, separated by 48 h. The first session was used to establish within-session reliability and variability. The first and second sessions were used to establish between-session reliability, variability, and the MDC. During each session, participants performed three five-second maximal isometric contractions in the bilateral squat, unilateral squat, bilateral standing plantarflexion, unilateral standing plantarflexion, bilateral seated plantarflexion, and unilateral seated plantarflexion positions (Figure 1). All unilateral tests were completed on the right limb only to limit the number of maximal isometric contractions within the testing session. Each five-second maximal isometric contraction within a position was separated by a 20 s recovery period. A further two-minute recovery period was provided once three maximal isometric contractions were completed within a position. A standardized and progressive warm-up was completed prior to testing, including bodyweight exercises and submaximal isometric contractions across the testing positions. The vGRF data were collected using a force platform (MUSCLELAB, Ergotest Innovation AS, Stathelle, Norway) sampling at 1000 Hz. An isometric rig, with 2.5 cm adjustable vertical spacing, and a barbell (Sportesse, Somerset, United Kingdom) were used for all tests, with a 3.3 cm thick foam pad (Power Guidance, London, England) around the barbell for comfort. Bodyweight was calculated from a five-second static trial where participants were standing motionless on the force platform. Participants were required to wear their own shoes (and the same shoes) for all

Figure 1: (A) Bilateral squat (B) Unilateral squat (C) Bilateral standing plantarflexion (D) Unilateral standing plantarflexion (E) Bilateral seated plantarflexion (F) Unilateral seated plantarflexion.

testing sessions. Participants were instructed to “push maximally into the barbell” before each trial. Each trial was initiated by the researcher instructing the participant to adopt the relevant position and then counting down “3, 2, 1, push”. The force platform was zeroed prior to each set.

2.3.1. Isometric Squat

The barbell was placed in a high-bar back squat position on the upper trapezius. Using a goniometer, knee and hip angles were measured to 140°, where full knee and hip extension were considered 180° (Brady et al., 2020). Knee angle was calculated by positioning the fulcrum of the goniometer over the lateral epicondyle of the femur, with the stabilization arm in line with the lateral malleolus and the movement arm in line with the greater trochanter. Hip angle was calculated by positioning the fulcrum of the goniometer over the greater trochanter with the stabilization arm in line with the femur and the movement arm in line with the glenohumeral joint. During bilateral tests, the feet were positioned at hip width. For unilateral tests, the contralateral limb was held in 90° of hip flexion to maintain a neutral hip position.

2.3.2. Isometric Standing Plantarflexion

The barbell was placed in a high-bar back squat position. Participants were instructed to adopt a “soft knee” position (170–180°) to avoid hyperextension. Participants were also instructed to adopt a “neutral” hip position (170–180°), measured by placing the fulcrum of the goniometer over the greater trochanter with the stabilization arm in line with the femur and the movement arm in line with the glenohumeral joint. The ankle was measured to 130° of plantarflexion where neutral was considered 90°. A plantarflexed position was selected over plantar grade or relative dorsiflexion to reduce the requirement of additional equipment (i.e., a heel raise block) and account for different heel drop heights across participant shoes. Ankle angle was calculated by positioning the fulcrum of the goniometer over the lateral malleolus with the stabilization arm in line with the head of the fibular and the movement arm in line with the first metatarsophalangeal joint. The ball of the foot was placed directly underneath the barbell. During bilateral tests, the feet were positioned at hip width. During unilateral tests, the contralateral limb position was the same as outlined in the squat protocol.

2.3.3. Isometric Seated Plantarflexion

The barbell was placed proximal to the patella on the quadriceps while participants were seated in 90° of knee and hip flexion. Knee and hip measurement techniques were consistent with those outlined in the squat and standing plantarflexion protocols. Ankle position was measured using the same methods outlined in the standing plantarflexion protocol. Participants were instructed to place their arms across their shoulders to avoid assistance from the upper limb. During bilateral tests, the feet were positioned at hip width. During unilateral tests, the contralateral limb was resting off the force platform to avoid assistance.

2.4. Statistical Analysis

Mean vGRF was extracted during static bodyweight trials and peak vGRF, hereon referred to as absolute vGRF, was extracted during maximal isometric trials directly from the force platform software. No filtering was applied to vGRF data. Body mass was calculated by dividing mean vGRF during the static bodyweight trial by the acceleration of gravity. Net and relative vGRF was calculated to account for the influence of body mass. Net vGRF was calculated by subtracting bodyweight from absolute vGRF. Relative vGRF was calculated by dividing the absolute vGRF by body mass. The mean ± standard deviation (SD) of the absolute, net, and relative vGRF was calculated from the three trials in each position.

The within-session reliability of absolute, net, and relative vGRF was established by calculating the ICCs, with 95% confidence intervals (CI), across the three trials in each position using the *irr* R package (Gamer et al., 2019). The between-session reliability of absolute, net, and relative vGRF (mean of the three trials) was established by calculating the ICCs, with 95% CI, across the two testing sessions in each position. Two-way mixed-effects models (type = agreement) were used to calculate ICCs for within- and between-session reliability (Koo & Li, 2016). The

Table 1: Within-session intraclass correlation coefficient and coefficient of variation.

		Absolute vGRF (N)		Net vGRF (N)		Relative vGRF ($N \cdot kg^{-1}$)	
Position	*n*	ICC (95% CI)	CV	ICC (95% CI)	CV	ICC (95% CI)	CV
DL Squat	18	0.99 (0.98–1.00)	2.9	0.99 (0.97–1.00)	4.1	0.97 (0.94–0.99)	2.9
SL Squat	18	0.98 (0.96–0.99)	3.5	0.98 (0.95–0.99)	5.2	0.96 (0.92–0.98)	3.5
DL Standing PF	18	0.96 (0.91–0.98)	4.4	0.94 (0.88–0.98)	6.5	0.92 (0.84–0.97)	4.4
SL Standing PF	18	0.97 (0.94–0.99)	3.2	0.96 (0.91–0.98)	5.2	0.93 (0.86–0.97)	3.2
DL Seated PF	18	0.94 (0.88–0.98)	6.1	-	-	0.93 (0.85–0.97)	6.1
SL Seated PF	18	0.95 (0.89–0.98)	5.4	-	-	0.93 (0.85–0.97)	5.4

Note: DL, Double-Leg; SL, Single-Leg; PF, Plantarflexion; ICC, Intraclass Correlation Coefficient; CV, Coefficient of Variation; vGRF, Vertical Ground Reaction Force; CI, Confidence Interval.

ICC was interpreted in line with Koo and Li (2016) where < 0.50 = poor; 0.50–0.75 = moderate; 0.75–0.90 = good; > 0.90 = excellent. The within- and between-session intra-subject variability of the absolute, net, and relative vGRF was established by computing the CV using the *EnvStats* R package (Millard, 2013). Standard error of measurement (SEM) was calculated using the following equation:

$$SEM = SD_{baseline}\sqrt{1 - ICC_{between}}$$

Where $SD_{baseline}$ was considered the between-subject SD of the absolute, net, and relative vGRF during the first testing session, and $ICC_{between}$ was considered the between-session ICC (Haley & Fragala-Pinkham, 2006). The MDC was calculated using the following equation:

$$MDC = 1.96 \times \sqrt{2} \times SEM$$

Following checks for outliers, normality, and equal variance, a paired samples Wilcoxon signed-rank test was used to investigate differences in the mean internal training load between sessions using the *stats* R package (R Core Team, 2020). All data processing and statistical analysis were conducted using R (version 4.0.3, R Foundation for Statistical Computing, Vienna, Austria).

3. Results

Differences in internal training load in the 48 h prior to the first (mean ± SD: 825 ± 886, range: 0–2460 Arbitrary Units [AU]) and second (mean ± SD: 1253 ± 1135, range: 200–3705 AU) data collection sessions ($Z = -2.5$, $p = .014$) was observed. The within- and between-session ICC, CV, SEM, and MDC of the absolute, net, and relative vGRF are reported in Tables 1 and 2. Mean ± SD and 95% confidence intervals for the absolute, net, and relative vGRF can be found in Table 3. Box plots and individual test-retest absolute, net, and relative vGRF data are shown in Figure 2. Box plots and individual differences in absolute, net, and relative vGRF between the bilateral and unilateral variations of each testing position can be seen in Figure 3.

4. Discussion

We examined the reliability, variability, and MDC of maximal isometric force tests across bilateral and unilateral variations of the squat, standing plantarflexion, and seated plantarflexion positions. We found excellent within- and between-session reliability (ICC ≥ 0.92) and low variability (CV ≤ 6.5%) for absolute, net, and relative vGRF across all testing positions. This is the first study to investigate the reliability, variability, and MDC of the absolute, net, and relative vGRF during the unilateral squat and the bilateral and unilateral ankle plantarflexion positions during maximal isometric force tests.

The within-session reliability and variability of vGRF measures observed during the bilateral and unilateral squat in the present study are in line with previous research investigating these positions (Bishop et al., 2019, 2021; Brady et al., 2020). We observed excellent between-session reliability (ICC ≥ 0.99) and low between-session CVs (≤ 2.8%) during the isometric bilateral squat. Three prior studies have investigated the between-session reliability of absolute vGRF during the bilateral squat and reported ICC values greater than 0.85; two studies investigated men (Blazevich & Gill, 2006; Drake et al., 2018), and one investigated women (Palmer et al., 2018). Only one study, however, used comparable equipment to the present investigation (Drake et al., 2018), with the remaining two studies using hack squat machines (Blazevich & Gill, 2006; Palmer et al., 2018). We demonstrate excellent between-session reliability (ICC ≥ 0.95) of vGRF measures during the unilateral squat, and bilateral and unilateral variations of standing and seated plantarflexion positions. The unilateral squat and unilateral plantarflexion positions have been investigated previously, typically demonstrating ICCs greater than 0.90 (Beckman et al., 2014; Bishop et al., 2021; Blazevich & Gill, 2006). These studies, however, have used bespoke equipment, such as a wall-mounted force platform, that may not be practical in applied environments. Our findings demonstrate that maximal isometric force tests across bilateral and unilateral variations of the squat, standing plantarflexion, and seated plantarflexion positions provide reliable measures of the absolute, net, and relative vGRF. Further, our findings support the notion that multiple test positions can be executed using a general isometric rig without the need for additional equipment.

Table 2: Between-session intraclass correlation coefficient, coefficient of variation, standard error of measurement, and minimal detectable change.

		Absolute vGRF (N)				Net vGRF (N)				Relative vGRF ($N \cdot kg^{-1}$)			
Position	*n*	ICC (95% CI)	CV	SEM (95% CI)	MDC (%)	ICC (95% CI)	CV	SEM (95% CI)	MDC (%)	ICC (95% CI)	CV	SEM (95% CI)	MDC (%)
DL Squat	18	1.00 (0.99–1.00)	2.0	49 (0–144)	135 (5.1)	1.00 (0.99–1.00)	2.8	51 (0–150)	140 (7)	0.99 (0.97–1.00)	2.4	0.8 (0.0–2.3)	2.2 (5.8)
SL Squat	18	0.99 (0.98–1.00)	3.3	58 (0–170)	159 (7.1)	0.99 (0.98–1.00)	5.1	59 (0–173)	162 (10)	0.97 (0.93–0.99)	3.4	1.0 (0.0–3.1)	2.9 (9.2)
DL Standing PF	18	0.99 (0.96–0.99)	3.3	80 (0–236)	221 (9.3)	0.98 (0.95–0.99)	4.8	82 (0–241)	226 (13)	0.96 (0.90–0.98)	3.4	1.2 (0.0–3.5)	3.3 (9.8)
SL Standing PF	18	0.98 (0.96–0.99)	3.0	55 (0–163)	152 (8.2)	0.97 (0.93–0.99)	4.9	56 (0–166)	156 (13)	0.96 (0.89–0.98)	3.0	0.8 (0.0–2.3)	2.1 (8.0)
DL Seated PF	18	0.97 (0.92–0.99)	4.8	100 (0–295)	276 (14.5)	-	-	-	-	0.97 (0.92–0.99)	4.8	1.2 (0.0–3.6)	3.4 (12.3)
SL Seated PF	18	0.97 (0.92–0.99)	5.9	51 (0–151)	141 (13.3)	-	-	-	-	0.95 (0.86–0.98)	6.0	0.8 (0.0–2.3)	2.2 (14.3)

Note: DL, Double-Leg; SL, Single-Leg; PF, Plantarflexion; ICC, Intraclass Correlation Coefficient; CV, Coefficient of Variation; SEM, Standard Error of Measurement; MDC, Minimal Detectable Change; vGRF, Vertical Ground Reaction Force; CI, Confidence Interval.

Table 3: Mean ± SD and 95% confidence intervals for peak and relative vertical ground reaction force.

			Absolute vGRF (N)		Net vGRF (N)		Relative vGRF ($N \cdot kg^{-1}$)	
Position	Sex	*n*	Mean ± SD	95% CI	Mean ± SD	95% CI	Mean ± SD	95% CI
DL Squat	Female	9	1859 ± 65	1816–1902	1290 ± 65	1248–1333	32.0 ± 1.2	31.3–32.8
	Male	9	3485 ± 83	3430–3539	2677 ± 83	2622–2731	42.7 ± 1.0	42.1–43.4
SL Squat	Female	9	1588 ± 55	1552–1623	1019 ± 55	983–1055	27.4 ± 1.0	26.8–28.1
	Male	9	2909 ± 100	2844–2975	2101 ± 100	2036–2166	35.8 ± 1.2	35.1–36.6
DL Standing PF	Female	9	1813 ± 54	1778–1849	1245 ± 54	1209–1280	31.2 ± 0.9	30.6–31.9
	Male	9	2941 ± 165	2833–3048	2132 ± 165	2025–2240	36.3 ± 2.0	35.0–37.6
SL Standing PF	Female	9	1474 ± 51	1441–1508	905 ± 51	872–939	25.5 ± 0.9	24.9–26.1
	Male	9	2221 ± 68	2177–2265	1413 ± 68	1369–1457	27.3 ± 0.8	26.8–27.9
DL Seated PF	Female	9	1477 ± 65	1434–1520	-	-	25.7 ± 1.1	25.0–26.5
	Male	9	2334 ± 178	2218–2451	-	-	29.0 ± 2.2	27.5–30.4
SL Seated PF	Female	9	825 ± 44	797–854	-	-	14.3 ± 0.8	13.8–14.8
	Male	9	1294 ± 62	1254–1335	-	-	16.0 ± 0.7	15.5–16.5

Note: DL, Double-Leg; SL, Single-Leg; PF, Plantarflexion; vGRF, Vertical Ground Reaction Force; CI, Confidence Interval.

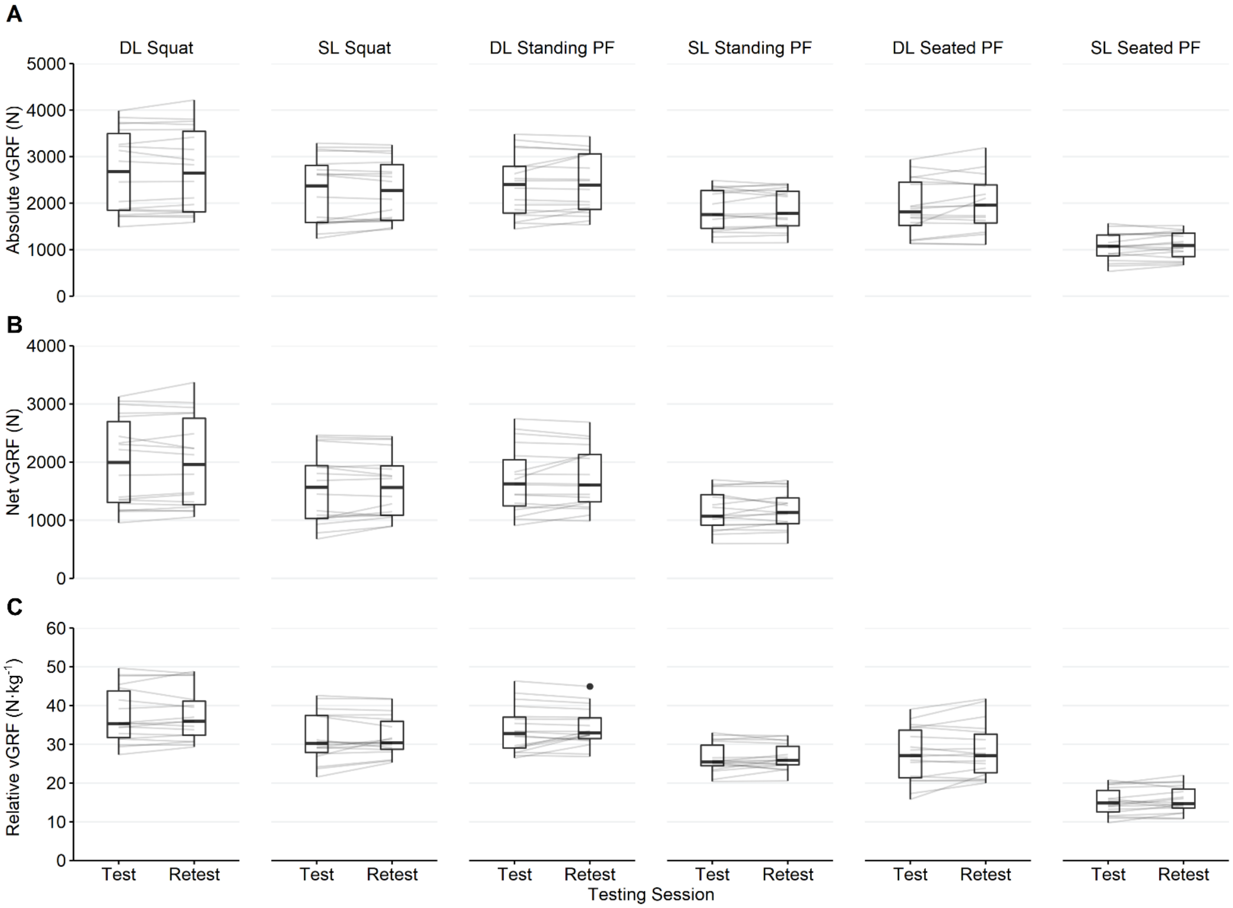

Figure 2: Box plots and individual test-retest absolute (A), net (B), and relative (C) vertical ground reaction force data. DL, Double-Leg; SL, Single-Leg; PF, Plantarflexion; vGRF, Vertical Ground Reaction Force.

The MDC for absolute vGRF ranged from 135 to 221 N (5.1–9.3% of the group mean) during bilateral and unilateral variations of the squat and standing plantarflexion positions. Previous research investigating the bilateral squat reported the MDC as 273 N (10.9%) and 230 N (~18.3%) in men and women, respectively (Drake et al., 2018; Palmer et al., 2018). Differences in study design may explain the ~100 N variation observed in the MDC between the present study and previous research. One study investigated larger knee angles using similar equipment (Drake et al., 2018), and one investigated comparable knee angles with different equipment (Palmer et al., 2018). Based on the utility of a general isometric rig in applied practice, we encourage future research to use similar equipment to the present study to facilitate comparisons. The MDC for absolute vGRF was 276 N (14.5%) and 141 N (13.3%) during bilateral and unilateral variations of seated plantarflexion, respectively. The higher MDC values (relative to the mean) may be attributed to the bar placement on the distal thigh, as it results in localized pressure and several participants reported discomfort during the test. Future research might investigate other setups, such as the use of a bespoke bar and pad that more evenly distributes pressure across the thigh.

In the present study, absolute vGRF was typically greater in the non-dancers, however, relative vGRF was typically greater in the professional dancers. Greater relative strength in the professional ballet dancers likely reflects the training requirements associated with being a professional athlete. Across all men, absolute vGRF observed during the bilateral squat aligns with those reported in male Division 1 football and track and field athletes (Nuzzo et al., 2008) and is ~500–1000 N greater than that of collegiate rugby union players, distance runners, and amateur boxers (Brady et al., 2020). For all women, absolute vGRF observed during the bilateral squat was comparable to those reported across various sports (Brady et al., 2018). Only two studies have investigated absolute vGRF during the unilateral squat, reporting values ~1000–1500 N lower than that observed in the present study (Beckman et al., 2014; Bishop et al., 2019). Two studies have investigated plantarflexion with an extended knee; one reported similar values in recreational dancers (Rice et al., 2017) and one reported values two-thirds of that observed in the present study in recreational athletes (Beckman et al., 2014). Two studies have investigated absolute vGRF during unilateral seated plantarflexion (Kanehisa et al., 1995; Pääsuke et al., 2000) and reported values comparable to the present study. The aforementioned studies, however, tested seated plantarflexion in relative dorsiflexion (as opposed to a plantarflexed position), which is associated with optimal force production of the plantar flexors (Sale et al., 1982). It should be

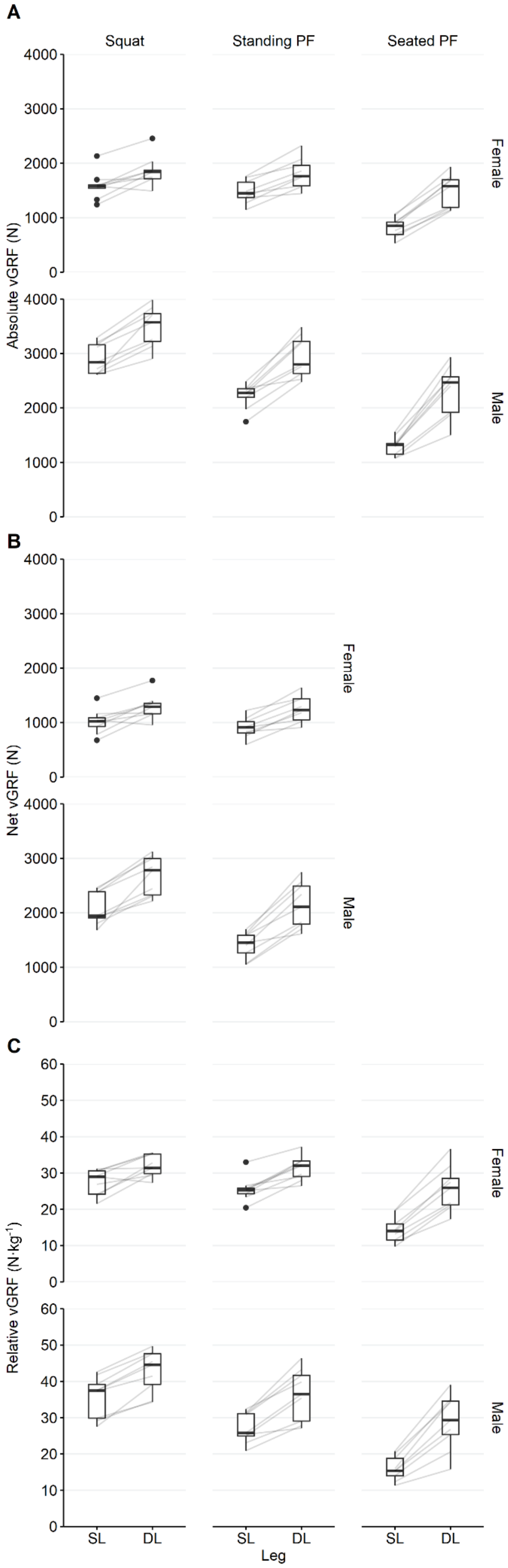

Figure 3: Box plots and individual differences in absolute (A), net (B), and relative (C) vGRF between unilateral and bilateral test positions across the squat, standing plantarflexion, and seated plantarflexion. DL, Double-Leg; SL, Single-Leg; PF, Plantarflexion; vGRF, Vertical Ground Reaction Force.

noted that although this may be associated with optimal force production, placing a participant in dorsiflexion will require additional equipment, such as a calf raise block, to ensure the heel is not in contact with the ground.

We did not outline any formal hypotheses regarding the effect of bilateral or unilateral stance on vGRF, however, we have observed several interesting findings that may direct future research. We observed relatively small differences in vGRF between bilateral and unilateral variations of the isometric squat (men: 19.9%; women: 18.2%) and standing plantarflexion position (men: 32.6%; women: 23.4%) but not seated plantarflexion position (men: 79.3%; women: 80.3%). We speculate that the limited increase in vGRF during the bilateral standing positions—compared to their unilateral counterparts—may be due to the participants' ability to transmit force through the trunk. Larger differences in vGRF were observed between bilateral and unilateral variations of the seated plantarflexion position where the trunk is not loaded. To that end, we speculate that greater muscle mass in the trunk and upper body may moderate the transmission of force to the lower extremity and result in greater vGRF during the bilateral test (Joseph et al., 2020; Prieske et al., 2016). Further research investigating differences in absolute vGRF between bilateral and unilateral variations of standing isometric force tests is warranted.

There are several limitations to this study, for example, there may have been fatigue or potentiation effects as the order in which isometric force tests were completed was not randomized. Tests were ordered to start with the highest vGRF and finish with the lowest vGRF (e.g., bilateral squat first and unilateral seated plantarflexion last). The internal training load 48 h prior to testing was significantly different between the two sessions. The between-session reliability and variability, however, were excellent, suggesting that these tests are robust to acute changes in internal training load. This supports previous findings suggesting that vGRF measures during the mid-thigh pull are appropriate for period monitoring, but may not be sensitive to detect acute changes in neuromuscular fatigue (Norris et al., 2019). The left limb was not tested, nor was limb dominance established, which may have revealed additional insights into the reliability associated with limb dominance (Matinlauri et al., 2019). Previous research has demonstrated differences in vGRF between dominant and non-dominant limbs during the unilateral squat, however, the effect size was small with differences in reported values of ~70 N (Bishop et al., 2021). Finally, the smallest possible vertical increment of the isometric rig was 2.5 cm, limiting the precise individual adjustment of bar height.

5. Practical Applications

This study demonstrates that bilateral and unilateral variations of the squat, standing plantarflexion, and seated plantarflexion positions provide reliable measures of the absolute, net, and relative vGRF. For simplicity, practitioners may wish to utilise one measure of vGRF in practice due to comparable reliability and variability across absolute, net, and relative vGRF. We observed similarities in vGRF between bilateral and unilateral variations of the isometric squat and standing plantarflexion positions. We speculate that bilateral variations of axially loaded tests may not reflect the true strength characteristics of the lower extremity and might be limited by the participants' ability to transmit higher forces through the trunk. The unilateral squat may therefore be a preferable test when aiming to measure lower extremity strength. Conversely, where an athlete's ability to transmit high forces through the entire kinetic chain in a bilateral stance is of interest, the inclusion of the bilateral squat in a testing battery is warranted. This study provides reference absolute, net, and relative vGRF data for men and women, alongside the MDC, which can facilitate criteria-based decision-making in applied environments.

6. Conclusion

This is the first study to investigate the within- and between-session reliability, variability, and the MDC of vGRF measures during bilateral and unilateral variations of the isometric squat, standing plantarflexion, and seated plantarflexion positions. All test positions demonstrated excellent within- and between-session reliability alongside low variability. The maximal isometric force tests investigated in the present study are a time-effective option to measure lower extremity vGRF using only a general isometric rig and force platform. Further, when interpreting a meaningful change, absolute vGRF values between 135–221 N (5.1 to 9.3% of the group mean) in standing and 141–276 N (13.3–14.5% of the group mean) in sitting can be used as benchmarks.

Conflict of Interest

The authors declare no conflict of interests. No funding was received for the completion of this study which forms part of the lead author’s PhD research.

Contributorship

All authors contributed to the conception and design of the work. AM and JS completed the data analysis. AM wrote the first draft and prepared all revisions. All authors reviewed and edited drafts and approved the final manuscript.

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Patient Involvement

There was no patient or public involvement in the design, conduct or reporting of this study.

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