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Testing Consistency: Analyzing the Reliability of Two Lower Limb Isometric Force Measurements in Strength-Trained Athletes

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Abstract: This study aimed to examine the intra- and inter-session reliability of kinetic variables in the isometric mid-thigh pull (IMTP) and isometric belt squat test (IBSqT) in strength-trained individuals. Fifteen men (26.9 ± 8.9 years; 1.78 ± 0.05 m; 86.9 ± 10.5 kg) and six women (23.8 ± 4.6 years; 1.66 ± 0.06 m; 65.8 ± 10.3 kg), experienced in strength training, completed a familiarization session followed by two experimental sessions. The peak force (PF) and relative peak force to body weight (RPF), were collected for both isometric tests. Additionally, force (F), impulse (I), and rate of force development (RFD) were analyzed across different time windows (50, 100, 150, 200, and 250 ms). The intraclass correlation coefficient (ICC), coefficient of variation (CV), standard error of measurement (SEM), smallest worthwhile change (SWC) and Bland-Altman plots were calculated and displayed. Intra-session reliability was excellent for PF and RPF (ICC ≥ 0.98, CV ≤ 10%) in both IMTP and IBSqT. However, RFD and IMP displayed higher variability (CV > 10%), with low to good reliability depending on time frames. Inter-session reliability was excellent for PF and RPF (ICC ≥ 0.96, CV ≤ 5.3%) in both tests. Force at various time points exhibited moderate to excellent reliability (ICC = 0.70–0.90). PF and RPF demonstrated the highest sensitivity to performance changes, with SWC0.2 values exceeding SEM. In contrast, RFD and impulse showed larger variabilities. These findings indicate that PF and RPF are the most reliable and sensitive metrics for monitoring performance. Coaches and practitioners can use IMTP and IBSqT to detect meaningful changes in maximal isometric force production.

Keywords: SEM; SWC; performance; neuromuscular; testing; RFD; testing; IMTP; time

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1. Introduction

Muscular strength is essential to support the primary motor actions involved in sports performance, such as vertical jumping, accelerations and decelerations, sprinting, or changes of direction [1]. For the optimal development of a training program, it is necessary that the neuromuscular performance, and specifically the muscular strength of the athlete, be regularly assessed and monitored in its various manifestations to observe adaptations or changes resulting from the training process [2]. Therefore, the appropriate selection of tests and variables to consider in the evaluation of muscular strength is a crucial aspect for the coach [3–5]. It is important to select muscular strength evaluation tests that not only measure what they intend to measure (i.e., are valid) but can also do so consistently and with a certain degree of reproducibility (i.e., are reliable) [6].

The methods used to assess maximum force generation capacity are classified according to the nature of this expression of strength, such as dynamic or static evaluations [7,8]. Maximum dynamic strength tests are used in the practical field, often evaluated using a one-repetition maximum (1 RM), which does not require sophisticated machinery, is reliable, and provides a valid method for determining maximum strength. However, some limitations must be considered, such as the subject's prior experience, the high neuromuscular demand, the fatigue that the test produces, and the time required to complete the test [9,10]. On the other hand, maximum isometric force evaluations, which represent the method of static maximum strength evaluation, are time-efficient, especially with large groups of athletes. However, they are less accessible as they require specific equipment, such as force platforms and specific racks, to measure the kinetic variables produced by the athlete during evaluation [11–13].

In recent years, the isometric mid-thigh pull (IMTP) has been advantageous for coaches and physical trainers since it is a test that produces minimal fatigue and generally takes less time than one-repetition maximum (1 RM) evaluation, while also being considered safe with a very low incidence of injury [14]. Specifically, the IMTP is a test that involves multiple joints to assess the athlete's isometric force capacity [11,15]. This test became popular for monitoring weightlifters, as the body position is meant to represent the second pull of the clean [16]. Additionally, maximal isometric force evaluation through the IMTP test has been shown to provide highly reliable and low-variable peak force (PF) results (intraclass correlation coefficient [ICC] = 0.89−0.99, coefficient of variation" [CV] = 1.7–5%), and it is possible to determine the smallest detectable change (SDC) around ~8.5% [13,17]. Recent reviews have documented the relationship between IMTP variables and other dynamic strength evaluation methods [13,18,19], showing strong correlations (r = 0.64–0.97) with 1 RM in clean and jerk, snatch, squat, and deadlift [16,20,21]. Similarly, high correlations have been evidenced with other dynamic performance tasks such as changes of direction (r = 0.57–0.85) [22], sprint kinetics (r = 0.48–0.73), and vertical jump height (r = 0.59–0.82) [23,24].

Another commonly used multi-joint maximal isometric force test, in the field of sports performance, is the isometric squat push test (ISqT). Athletes can maintain a squat position at knee angles of 90°, 120°, or 140°, providing a maximum isometric effort for a given period. Although IMTP is more widely used due to its strong scientific background [8], ISqT also provides highly reliable and low-variable PF results (ICC = 0.97−0.99, CV = 3.6%), with an SDC of approximately ~11% [17,18,25]. An isometric squat push test, like IMTP, has been compared with dynamic maximum strength tests and other sports tasks, showing similar correlations [25,26]. However, absolute and relative force values in ISqT have been found to be significantly higher compared to IMTP, even when using the same knee angle (140°) [27]. Researchers theorize that this may be due to the elimination of upper limb involvement as a means of anchoring and pulling on the bar, along with instructions to push instead of pull [24,27].

To date, and to our knowledge, few studies have explored the possibility of evaluating multi-joint maximal isometric force by eliminating the bar as an object of traction (IMTP) or push (ISqT). Layer et al. [28] included the isometric belt squat test (IBSqT) and compared kinetic variables with those of ISqT. The authors reported that the isometric belt squat test produced higher values in all variables (Relative peak Force [N/kg] 2.67 ± 0.56 vs. 3.15 ± 0.82), except for hip angular moment, where no significant differences were found ($p > 0.05$). Although the study by Layer et al. [28] provides information on interesting variables, it does not provide data on important metrics for sports performance, nor does it address the reliability and consistency of these results. On the other hand, Varela-Olalla et al. [29] conducted a validation study of a commercial device using an isometric belt squat test in different positions and angles (90°, 105°, and 120°) but did not report the reliability data for time-dependent variables. Given that prior studies, such as those by Layer et al. [28] and Varela-Olalla et al. [29], did not address the reliability and consistency of isometric belt squat test results or time-dependent variables, there remains a clear need for further research to establish the reliability of this method in evaluating multi-joint maximal isometric force across various conditions.

The isometric belt squat test exhibits distinct methodological approaches to evaluating lower limb strength compared to IMTP and the isometric squat. The IBSqT isolates the lower body by removing upper-body involvement, avoiding grip strength limitations, and enabling higher force outputs [27]. Its hip-based load placement minimizes lumbar torque, enhancing safety and accessibility [28]. However, direct comparisons of the reliability of force production between these tests are absent in the scientific literature, necessitating further research to establish their relative reliability. Identifying an accessible, efficient, and reliable method like the IBSqT could streamline testing and reduce the reliance on specialized equipment used in protocols like the IMTP. Furthermore, the IBSqT offers a safer, time-efficient alternative for assessing strength, which is crucial for in-season monitoring where minimizing athlete fatigue and injury risk is paramount. Therefore, this study aims to compare the intra- and inter-session reliability of kinetic variables at several time windows between the IBSqT and the IMT in strength-trained individuals.

2. Materials and Methods

2.1. Experimental Approach to the Problem

This cross-sectional study employed a repeated-measures within-subject design, where the IBSqT and IMTP tests were conducted across three sessions with a one-week separation between trials (Figure 1) to examine and compare the intra- and inter-session reliability of the kinetic variables PF, RPF, RFD 0–50; 0–100; 0–150; 0–200; 0–250, Force at 50; 100; 150; 200; 250 ms, and IMP 0–50; 0–100; 0–150; 0–200; 0–250 ms in the IMTP and IBSqT, performed in an optimal pushing position, in individuals with strength training experience. The procedures were identical on each testing day, except that the initial test order was randomized to eliminate order bias. Subjects were asked to refrain from strenuous exercise for at least 24 h prior to testing. All tests were performed between 11 a.m. and 2 p.m. to avoid variations in circadian rhythms [30].

Figure 1. Lateral and frontal view of both isometric tests.

2.2. Subjects

Fifteen men (26.9 ± 8.9 years; 1.78 ± 0.05 m; 86.9 ± 10.5 kg) and six women (23.8 ± 4.6 years; 1.66 ± 0.06 m; 65.8 ± 10.3 kg) with at least two years of strength training experience volunteered for this study. None of the participants had physical limitations, health issues, or musculoskeletal injuries that could interfere with the tests. Participants who exceeded the 7-day interval between sessions were excluded from the study. They were informed about the study procedures and signed written informed consent before beginning the study. The study protocol adhered to the principles of the Declaration of Helsinki.

2.3. Procedure

Subjects attended the laboratory on three separate occasions, with sessions 2 and 3 spaced no more than 7 days apart. The first visit included an explanation of the research purpose, familiarization with the tests, and determination of the optimal position for each test. The optimal position was defined as the one where the subject could apply the maximum force level. On each testing day, subjects performed a standardized 6-min warm-up focusing on joint mobility, with an emphasis on ankle, hip, and thoracic mobility. This was followed by six muscle activation exercises targeting various muscle groups (knee flexion-extension, isometric squats, hip flexion, lunges, bodyweight squats, and barbell squats using a 20 kg Olympic bar). Subjects performed 8 repetitions per exercise, except for the isometric squat, which lasted 20 s. Each participant then performed a specific IMTP warm-up, as previously described in the literature [11], consisting of pulling the IMTP bar for 5 s at 50% self-directed effort, 3 s at 70–80%, and 3 s at 90% of maximum effort, with 1 min of recovery between warm-up efforts. The same warm-up protocol was used for the isometric belt squat test. Three maximal attempts were performed for each test, with 3 min of rest between repetitions. A photograph was taken from the sagittal plane for each test (iPhone 12, iOS 16.3.1, Apple, Cupertino, CA, USA), and the instantaneous knee and hip joint angles were quantified using the "Angle meter" mobile app.

2.4. Isometric Mid-Thigh Pull

The IMTP test was performed with a portable isometric pulling rack, and the vertical ground reaction force (vGRF) applied to the body's center of mass during each test was recorded using a wireless dual-force plate system with a sampling frequency of 1000 Hz (Hawkin Dynamics Inc., Westbrook, ME, USA). The system was mounted on a custom-designed rack (Sorinex, Inc., Irmo, SC, USA) to fix the bar at any height above the force platforms. The starting position was explained and demonstrated by the researchers, mimicking the second pull of a clean [11]. This position allowed athletes to maintain a knee angle of 132.5 ± 6° and a hip angle of 133.5 ± 9°. The bar height was individually set during the familiarization session, and subjects were provided with lifting straps to ensure that grip did not affect performance [31]. Once in the optimal position with some pretension, a tablet (Samsung TAB7, Seoul, Republic of Korea) with force platform software displayed the real-time force-time curve (Figure 1). Upon receiving the software's start signal, subjects began generating maximum force. Verbal and visual encouragement was provided to ensure maximal effort. Before and during each test, subjects were instructed to "pull or push as hard and fast as possible" to achieve the highest possible PF and RFD [32].

2.5. Isometric Belt Squat Test

The isometric belt squat test was performed on the same wireless dual-force plate system (1000 Hz sampling rate, Hawkin Dynamics Inc.) that recorded the vertical ground reaction force (vGRF). During execution, the force plates were placed over a metal structure with a ring and harness to attach the chain to the strength belt. In the familiarization session, subjects standardized their optimal pushing position (knee angle of $125.2 \pm 8.2°$ and hip angle of $108.3 \pm 10.6°$), and the corresponding chain link for the optimal force position was recorded for subsequent sessions. The participant was instructed on the importance of generating pretension in the chain to avoid any morphological alteration in the force-time relationship; otherwise, the test would be invalidated. Once in the optimal position with pretension, a 7-inch tablet (Samsung TAB7, Seoul, Republic of Korea) displayed the real-time force-time curve via the force platform software. After the start signal, participants generated maximum force. Verbal and visual encouragement was provided to ensure maximal effort. Participants were instructed to "pull or push as hard and fast as possible" before and during each test to achieve the highest possible PF [32].

2.6. Force-Time Curve Data Analysis

Vertical ground reaction force (vGRF) and its integration over time (force-time) were recorded using a wireless Hawkin Dynamics Inc. system with dual-force platforms at a 1000 Hz sampling rate for both isometric tests (Figure 2). The Hawkin Dynamics software (v. 2.1) runs on an Android tablet, connects via Bluetooth to the force platforms, and automatically analyzes vGRF before transferring data via WiFi to the Hawkin Dynamics cloud server. The accuracy of the hardware [33] and software [34] has been validated in previous studies. The force platforms were placed on a flat and level surface, and were reset to zero before each test. The onset of maximum force production for each trial was identified when the vGRF exceeded the reference force reading by >3 SDs. Maximum force in both tests was calculated as the highest gross force produced during the test (Figure 1). Each participant's maximum force was also divided by their body mass to provide a relative force score (relative maximum force). Body mass was automatically recorded using a "weighing" application on the force plates, where participants stood still for 1 s, and body mass was calculated as the lowest 1-s average of vGRF during weighing, identified by an optimization loop. Body mass was calculated by dividing body weight by the acceleration due to gravity ($9.81\ m{\cdot}s^2$). The RFD (calculated as the average slope of vGRF applied during the isometric test between the onset and post-onset of all time windows) was also recorded to better capture the participants' rapid force production abilities. The average of the three recorded trials was used for statistical analysis.

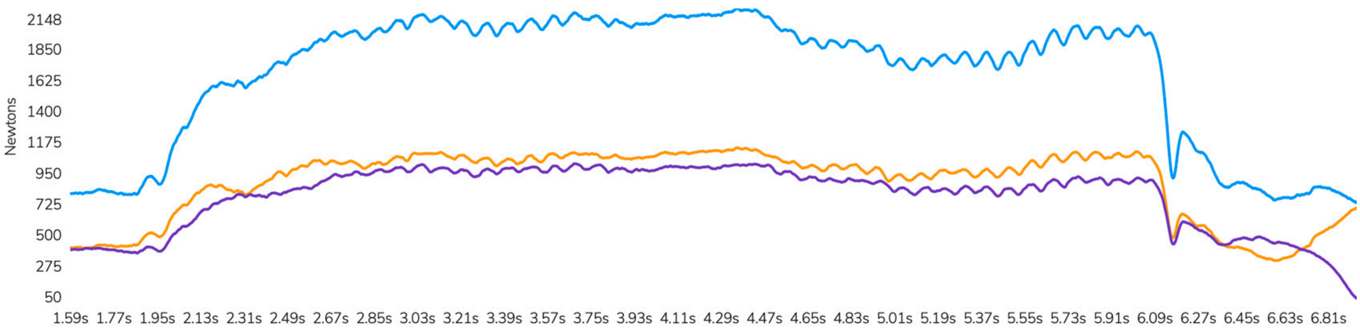

Figure 2. Isometric F-T curve representative of a participant. The purple line represents the vGRF of the left leg, the orange line represents the vGRF of the right leg, and the blue line represents the sum of both vGRFs.

2.7. Statistical Analysis

Descriptive characteristics were calculated, and the results were presented as means and standard deviations (SD). All the force-time data were analyzed using a custom spreadsheet. G*Power software (v3.1.9.7) was used to calculate the statistical power post hoc. The correlation: the point biserial model statistical test was applied, with a coefficient of determination (r^2) of 0.69 for the peak force during the IMTP. The alpha error was set at 0.05, and the sample consisted of 21 subjects. The calculations indicated that the statistical power of the analysis was 0.98. The Shapiro–Wilk test was performed to assess data normality. Levene's test was used to verify the homogeneity of the analyzed variables. ICC (3.1 model), CV, and 95% CIs were calculated to assess the intra- and inter-session reliability of both tests using a custom Excel spreadsheet [35]. Reliability was categorized as follows: ICC $\leq$ 0.5 indicated poor reliability, values $\leq$ 0.75 indicated moderate reliability, values $\leq$ 0.9 indicated good reliability, and values > 0.90 indicated excellent reliability [36]. The acceptable CV threshold was set at $\leq$10% [37]. Paired *t*-tests with a significance level of $p \leq 0.05$ were used to determine if there were differences in PF, RPF, RFD 0–50; 0–100; 0–150; 0–200; 0–250, Force at 50; 100; 150; 200; 250 ms, and impulse 0–50; 0–100; 0–150; 0–200; 0–250 produced by IMTP and IBSqT across sessions. Hedges' g was used to determine the effect size of group differences in test-retest scores, using Cohen's scale as trivial ($g < 0.2$), small ($0.2 \leq g < 0.5$), moderate ($0.5 \leq g < 0.8$), and large ($g \geq 0.8$) [38]. The standard error of measurement (SEM) provided an indication of score precision [39] and was used to understand whether differences in measurements were real or due to error [37]. The smallest worthwhile change (SWC) was determined by multiplying the between-subject SD by 0.2 (SWC0.2), which represents a typical small effect, or 0.5 (SWC0.5) for a medium effect [40]. SWC/SEM was calculated to determine whether a test could detect changes greater than the error, with values below 1.0 indicating that it was unlikely for the measure to detect changes larger than the error [41]. The limits of agreement corresponding to 1.96 SD of the bias (LoA) and 95% CI between the test-retest evaluations were determined from Bland–Altman plots. All statistical analyses were performed using IBM SPSS v26 statistical software (SPSS Inc., Chicago, IL, USA) and GraphpadPrism v9.

3. Results

3.1. Intra-Session Reliability in IMTP

Descriptive statistics for the variables analyzed during the first session of IMTP measurements are presented in Table 1. Peak force (PF) and rate of peak force (RPF) demonstrated excellent reliability values for IMTP (ICC = 0.98) and acceptable variability with a coefficient of variation (CV) $\leq$ 10% (Table 1). However, variables associated with the rate of force development (RFD), force at specific time points, and impulse showed values ranging from low to good reliability across all analyzed time windows, displaying significant variability within the session (CV > 10%). Additionally, PF and RPF exhibited good sensitivity to performance changes, as the SWC0.2 scores were higher than SEM.

3.2. Intra-Session Reliability in Isometric Belt Squat Test

Descriptive statistics for the variables analyzed during the first session of IBSqT measurements are shown in Table 2. PF and RPF have demonstrated excellent reliability values for IBSqT (0.95–0.97) and acceptable variability with CV $\leq$ 10% (Table 2). The variable force at 50 ms (ICC = 0.89) shows acceptable variability (CV = 9.6%); however, as the time window for this variable increases, the results tend to become more dispersed with CV >10%. RFD across all its time windows shows good to excellent ICC values, but none of the variables meet the acceptable variability criterion of CV $\leq$ 10%. For impulse (IMP), all time windows demonstrated ICC values ranging from good to excellent with CV $\leq$ 10%, except for IMP0–150 (ICC = 0.79; CV = 14.5%). Furthermore, RPF showed good sensitivity to performance changes, as SWC0.2 scored higher than SEM.

Table 1. Intra-session reliability of IMTP.

	Mean	SD	CV% (95%CI)	ICC (95%CI)	SEM (95%CI)	SWC 0.2 (95%CI)
Peak force (N)	2964.7	756.5	4.2 (3.4–5.7)	0.98 (0.95–0.99)	126.0 (101.3–168.0)	149.2 (85.1–190.9)
Relative peak force (N/kg)	37.6	11.3	4.3 (3.4–5.7)	0.98 (0.96–0.99)	1.6 (1.3–2.1)	2.2 (1.3–2.9)
Force at 50 ms (N)	1391.8	376.0	13.4 (10.7–17.8)	0.77 (0.58–0.89)	186.0 (149.6–248.0)	65.4 (42.1–88.0)
RFD 0–50 ms (N·s)	5756.5	4808.5	32.6 (26.2–43.5)	0.86 (0.72–0.93)	1878.3 (1510.7–2505.1)	885.3 (539.8–1164.0)
Impulse 0–50 ms (N·s)	61,724.9	13,861.7	11.8 (9.5–15.7)	0.74 (0.53–0.87)	7261.7 (5840.4–9685.3)	2361.5 (1549.5–3206.6)
Force at 100 ms (N)	1669.3	535.4	15.8 (12.7–21.1)	0.77 (0.58–0.89)	264.5 (212.7–352.8)	93.1 (59.9–125.3)
RFD 0–100 ms (N·s)	5786.0	3933.9	26.5 (21.3–35.3)	0.86 (0.73–0.93)	1533.5 (1233.4–2045.3)	724.5 (441.6–952.5)
Impulse 0–100 ms (N·s)	138,663	35,875	13.0 (10.5–17.4)	0.76 (0.56–0.88)	18,070.9 (14,534.2–24,102.3)	6198.1 (4013.8–8366.2)
Force at 150 ms (N)	1858.9	614.0	18.1 (14.5–24.1)	0.72 (0.49–0.86)	335.9 (270.2–448.0)	102.8 (68.6–140.6)
RFD 0–150 ms (N·s)	4668.7	2471.8	33.0 (26.5–44.0)	0.63 (0.37–0.81)	1540.9 (1239.3–2055.2)	386.5 (274.6–545.1)
Impulse 0–150 ms (N·s)	225,651	63,879	14.3 (11.5–19.1)	0.76 (0.56–0.88)	32,348.5 (26,017.4–43,145.2)	11,016.5 (7146.2–14,881.3)
Force at 200 ms (N)	2074.3	672.4	18.9 (15.2–25.2)	0.68 (0.44–0.84)	391.2 (314.6–521.8)	109.4 (74.9–151.5)
RFD 0–200 ms (N·s)	5253.1	2523.1	27.3 (21.9–36.4)	0.70 (0.46–0.85)	1433.4 (1152.9–1911.8)	415.3 (281.4–572.4)
Impulse 0–200 ms (N·s)	323,426	95,099	15.5 (12.5–20.7)	0.74 (0.52–0.87)	50,281.7 (40,440.9–67,063.8)	16,143.8 (10,628.0–21,954.7)
Force at 250 ms (N)	2214.8	661.1	16.5 (13.3–22.1)	0.71 (0.48–0.85)	366.2 (294.5–488.4)	110.1 (73.8–151.0)
RFD 0–250 ms (N·s)	4636.4	1970.8	16.6 (13.3–22.1)	0.86 (0.73–0.93)	767.4 (617.2–1023.5)	363.1 (221.2–477.2)
Impulse 0–250 ms (N·s)	431,115.5	127,627.6	15.9 (12.8–21.2)	0.73 (0.51–0.86)	68,588.7 (55,164.9–91,480.9)	21,526.2 (14,257.1–29,355.9)

IMTP: Isometric Mid-Thigh Pull; SD: Standard Deviation; CV%: Coefficient of Variation; ICC: Intraclass Correlation Coefficient; SEM: Standard Error of Measurement; SWC: Smallest Worthwhile Change; N: Newton; N/kg: Newton per kilogram); N·s: Newton-second.

Table 2. Intra-session reliability of isometric belt squat test.

	Mean	SD	CV% (95%CI)	ICC (95%CI)	SEM (95%CI)	SWC 0.2 (95%CI)
Peak force (N)	5148.9	1332.8	6.1 (4.9–8.2)	0.95 (0.89–0.98)	316.4 (254.5–422.0)	258.9 (149.9–333.3)
Relative peak force (N/kg)	65.8	21.9	6.0 (4.8–8.0)	0.97 (0.94–0.99)	3.9 (3.2–5.3)	4.3 (2.5–5.5)
Force at 50 ms (N)	1539.1	432.3	9.6 (7.7–12.8)	0.89 (0.78–0.95)	148.0 (119.0–197.4)	81.2 (48.6–105.9)
RFD 0–50 ms (N·s)	6698.3	5888.1	26.3 (21.2–35.1)	0.90 (0.80–1.00)	1763.0 (1418.0–2351.4)	1123.6 (661.8–1456.3)
Impulse 0–50 ms (N·s)	66,154.6	14,580.7	9.3 (7.5–12.4)	0.84 (0.68–0.92)	6128.0 (4928.6–8173.2)	2646.1 (1635.7–3499.4)
Force at 100 ms (N)	2003.8	800.6	11.4 (9.1–15.1)	0.93 (0.85–0.97)	227.5 (182.9–303.4)	153.5 (90.0–198.6)
RFD 0–100 ms (N·s)	8406.5	6606.1	26.2 (21.0–34.9)	0.90 (0.80–0.95)	2199.7 (1769.2–2933.9)	1245.8 (742.2–1622.3)
Impulse 0–100 ms (N·s)	156,359	48,200	8.6 (6.9–11.4)	0.93 (0.86–0.97)	13,417.9 (10,791.8–17,896.3)	9258.9 (5418.3–11,969.5)
Force at 150 ms (N)	2301.6	871.0	19.3 (15.5–25.7)	0.76 (0.55–0.88)	443.1 (356.4–591.0)	150.0 (97.4–202.7)
RFD 0–150 ms (N·s)	7290.9	4866.3	22.2 (17.9–29.7)	0.90 (0.80–0.95)	1621.1 (1303.8–2162.1)	917.7 (546.8–1195.0)
Impulse 0–150 ms (N·s)	257,938	78,587	14.5 (11.6–19.3)	0.79 (0.60–0.90)	37,358.5 (30,046.9–49,827.3)	13,827.9 (8802.2–18,522.0)
Force at 200 ms (N)	2634.4	959.3	12.6 (10.1–16.8)	0.89 (0.78–0.95)	331.9 (267.0–442.7)	180.0 (107.8–234.9)
RFD 0–200 ms (N·s)	7491.9	3930.4	16.5 (13.3–22.0)	0.91 (0.82–0.96)	1237.8 (995.5–1650.9)	746.1 (441.7–969.0)
Impulse 0–200 ms (N·s)	391,072	138,111	9.7 (7.8–13.0)	0.93 (0.86–0.97)	38,024.7 (30,582.7–50,715.9)	26,554.6 (15,525.9–34,316.2)
Force at 250 ms (N)	2908.3	969.7	13.0 (10.4–17.3)	0.86 (0.73–0.93)	376.7 (303.0–502.5)	178.7 (108.9–234.9)
RFD 0–250 ms (N·s)	6980.6	3336.7	19.9 (16.0–26.5)	0.84 (0.69–0.92)	1387.2 (1115.7–1850.2)	606.9 (374.4–801.9)
Impulse 0–250 ms (N·s)	540,461.9	173,484.7	8.7 (7.0–11.6)	0.93 (0.86–0.97)	47,029.1 (37,824.8–62,725.5)	33,397.7 (19,503.1–43,138.4)

IMTP: Isometric Mid-Thigh Pull; SD: Standard Deviation; CV%: Coefficient of Variation; ICC: Intraclass Correlation Coefficient; SEM: Standard Error of Measurement; SWC: Smallest Worthwhile Change; N: Newton; N/kg: Newton per kilogram); N·s: Newton-second.

3.3. Between-Session Reliability in IMTP

Between-session IMTP SEM, SWC0.2, and effect size (ES), are presented in Table 3. Similar to intra-session tests, PF and RPF demonstrated excellent reliability values (ICC = 0.96; 0.99) and acceptable variability (5.3–3.2%). Force at all its time points demonstrated good reliability (ICC = 0.77; 0.84) with variability values around 10.8–13.6%. For RFD, ICC values range from poor to excellent (0.33–0.94), with CV ranging from 10.1% to 42%. IMP 0–50 ms showed good reliability (ICC = 0.80) and met the acceptable variability criterion (CV = 8.7%), while other time windows showed good reliability (ICC = 0.78–0.79), with CV ranging from 10.3% to 11.8%. Paired *t*-tests showed no significant differences between test sessions for all kinetic variables ($p > 0.05$). Additionally, RPF demonstrated good sensitivity to performance changes, with SWC0.2 scoring higher than SEM. For IMTP, the average bias for peak force (PF) was −36.47 N, with a bias SD of 210.9 N and 95% LoA −449.7 N and 376.8 N. For the body mass-relative measurement (PF/BM), IMTP showed an average bias of −0.2802 N/kg, with narrow LoA between −5.714 N/kg and 5.153 N/kg. Regarding the force at 50 ms, IMTP showed a bias of −29.23 N, with an SD of 169 N and LoA between −360.5 N and 302 N. In terms of RFD at 50 ms, IMTP presented an average bias of 531 N, with wide LoA between −4053 N and 5115 N. At 150 ms, the force showed a bias of −43.65 N, with LoA between −602.3 N and 515 N. The RFD at 150 ms showed a bias of −96.52 N, with LoA ranging from −2621 N to 2428 N. For impulse at 150 ms, IMTP showed a bias of −5700 N·ms, with extremely wide LoA ranging from −63,908 N·ms to 52,508 N·ms. At 250 ms, the force showed a positive bias of 33.57 N, with LoA between −629 N and 696.1 N. The RFD at 250 ms showed a bias of 234 N, with LoA ranging from −1033 N to 1501 N. For impulse at 250 ms, IMTP presented a bias of 593.1 N·ms, with LoA ranging from −140,137 N·ms to 141,323 N·ms. All these data are displayed in Figures 3–6.

Table 3. Inter-session reliability of IMTP.

	CV% (95%CI)	ICC (95%CI)	SEM (95%CI)	SWC 0.2 (95%CI)	*p* Value	ES (g) (95%CI)
Peak force (N)	5.3 (4.1–7.7)	0.96 (0.90–0.98)	158.8 (121.5–229.3)	148.4 (113.6–214.4)	0.737	−0.02 (−0.65 to 0.60)
Relative peak force (N/kg)	6.0 (4.8–8.0)	0.97 (0.94–0.99)	3.9 (3.2–5.3)	4.3 (2.5–5.5)	0.849	−0.01 (−0.63 to 0.62)
Force at 50 ms (N)	9.6 (7.7–12.8)	0.89 (0.78–0.95)	148.0 (119.0–197.4)	81.2 (48.6–105.9)	0.995	0.00 (−0.62 to 0.62)
RFD 0–50 ms (N·s)	26.3 (21.2–35.1)	0.90 (0.80–1.00)	1763.0 (1418.0–2351.4)	1123.6 (661.8–1456.3)	0.159	0.25 (−0.37 to 0.88)
Impulse 0–50 ms (N·s)	9.3 (7.5–12.4)	0.84 (0.68–0.92)	6128.0 (4928.6–8173.2)	2646.1 (1635.7–3499.4)	0.440	−0.11 (−0.74 to 0.51)
Force at 100 ms (N)	11.4 (9.1–15.1)	0.93 (0.85–0.97)	227.5 (182.9–303.4)	153.5 (90.0–198.6)	0.747	−0.05 (−0.67 to 0.58)
RFD 0–100 ms (N·s)	26.2 (21.0–34.9)	0.90 (0.80–0.95)	2199.7 (1769.2–2933.9)	1245.8 (742.2–1622.3)	0.868	0.02 (−0.61 to 0.64)
Impulse 0–100 ms (N·s)	8.6 (6.9–11.4)	0.93 (0.86–0.97)	13,417.9 (10,791.8–17,896.3)	9258.9 (5418.3–11,969.5)	0.565	−0.09 (−0.71 to 0.54)
Force at 150 ms (N)	19.3 (15.5–25.7)	0.76 (0.55–0.88)	443.1 (356.4–591.0)	150.0 (97.4–202.7)	0.948	0.01 (−0.61 to 0.63)
RFD 0–150 ms (N·s)	22.2 (17.9–29.7)	0.90 (0.80–0.95)	1621.1 (1303.8–2162.1)	917.7 (546.8–1195.0)	0.304	−0.26 (−0.89 to 0.36)
Impulse 0–150 ms (N·s)	14.5 (11.6–19.3)	0.79 (0.60–0.90)	37,358.5 (30,046.9–49,827.3)	13,827.9 (8802.2–18,522.0)	0.925	−0.01 (−0.64 to 0.61)
Force at 200 ms (N)	12.6 (10.1–16.8)	0.89 (0.78–0.95)	331.9 (267.0–442.7)	180.0 (107.8–234.9)	0.805	0.04 (−0.59 to 0.66)

Table 3. *Cont.*

	CV% (95%CI)	ICC (95%CI)	SEM (95%CI)	SWC 0.2 (95%CI)	*p* Value	ES (g) (95%CI)
RFD 0–200 ms (N·s)	16.5 (13.3–22.0)	0.91 (0.82–0.96)	1237.8 (995.5–1650.9)	746.1 (441.7–969.0)	0.273	0.12 (−0.50 to 0.75)
Impulse 0–200 ms (N·s)	9.7 (7.8–13.0)	0.93 (0.86–0.97)	38,024.7 (30,582.7–50,715.9)	26,554.6 (15,525.9–34,316.2)	0.936	−0.01 (−0.64 to 0.61)
Force at 250 ms (N)	13.0 (10.4–17.3)	0.86 (0.73–0.93)	376.7 (303.0–502.5)	178.7 (108.9–234.9)	0.654	0.06 (−0.57 to 0.68)
RFD 0–250 ms (N·s)	19.9 (16.0–26.5)	0.84 (0.69–0.92)	1387.2 (1115.7–1850.2)	606.9 (374.4–801.9)	0.113	0.12 (−0.50 to 0.75)
Impulse 0–250 ms (N·s)	8.7 (7.0–11.6)	0.93 (0.86–0.97)	47,029.1 (37,824.8–62,725.5)	33,397.7 (19,503.1–43,138.4)	0.700	0.01 (−0.62 to 0.63)

IMTP: Isometric Mid-Thigh Pull; SD: Standard Deviation; CV%: Coefficient of Variation; ICC: Intraclass Correlation Coefficient; SEM: Standard Error of Measurement; SWC: Smallest Worthwhile Change; N: Newton; N/kg: Newton per kilogram); N·s: Newton-second.

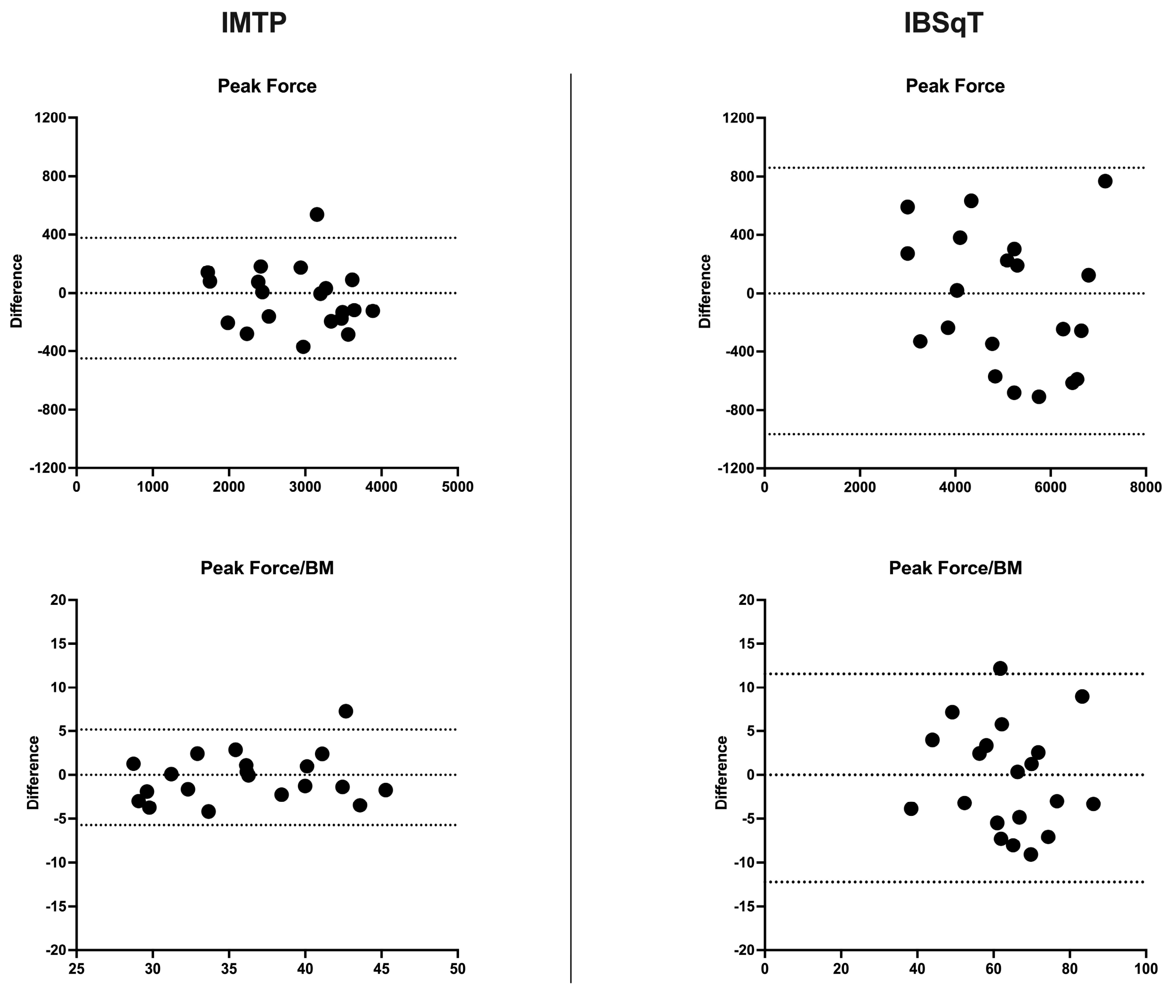

Figure 3. Bland–Altman plots of peak force and peak force relative to body weight in the isometric mid-thigh pull (IMTP) and isometric belt squat test (IBSqT). Dashed lines represent the value of zero and the limits of agreement for the test-retest evaluations.

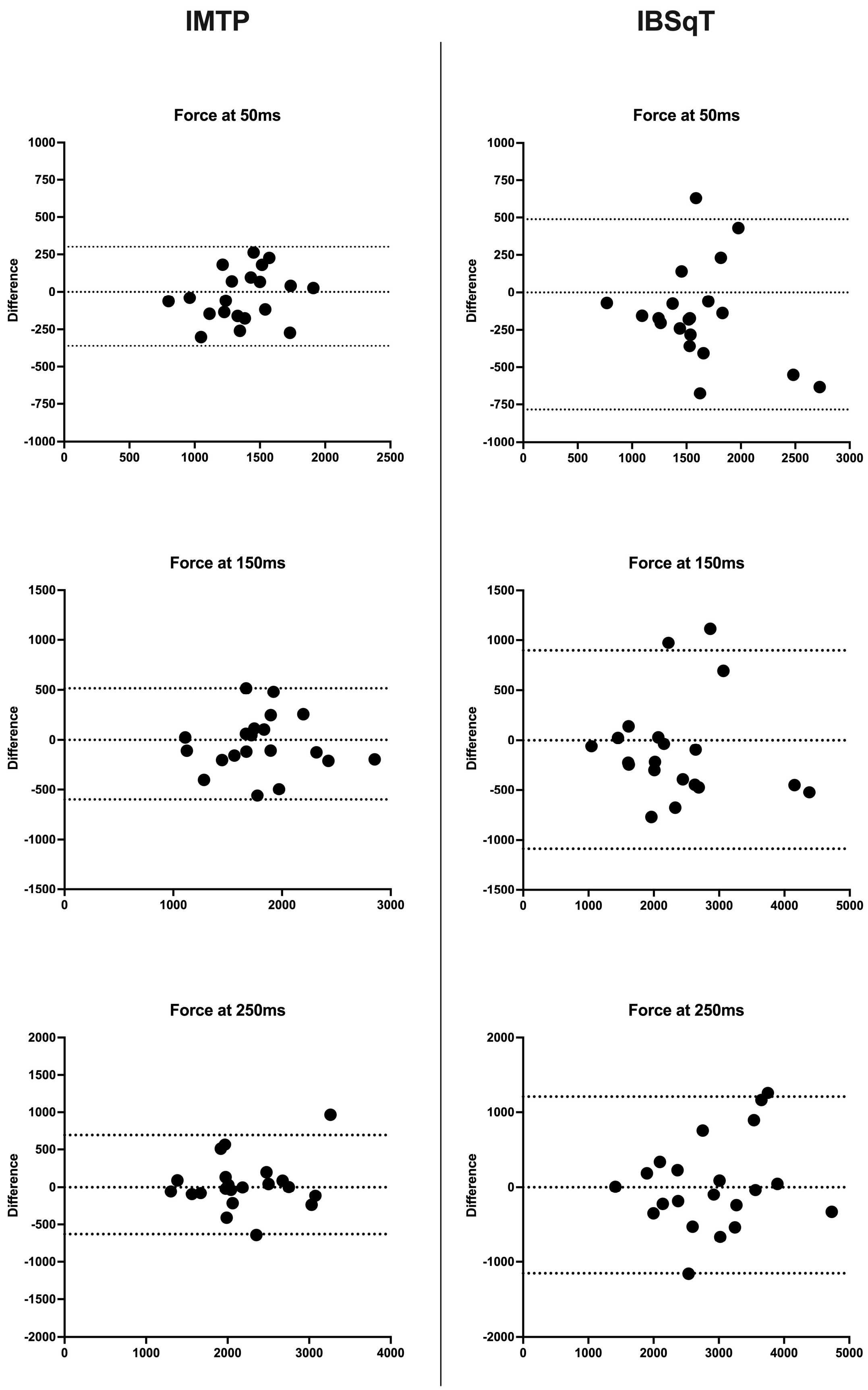

Figure 4. Bland–Altman plots of force production at different time windows. Dashed lines represent the value of zero and the limits of agreement for the test-retest evaluations.

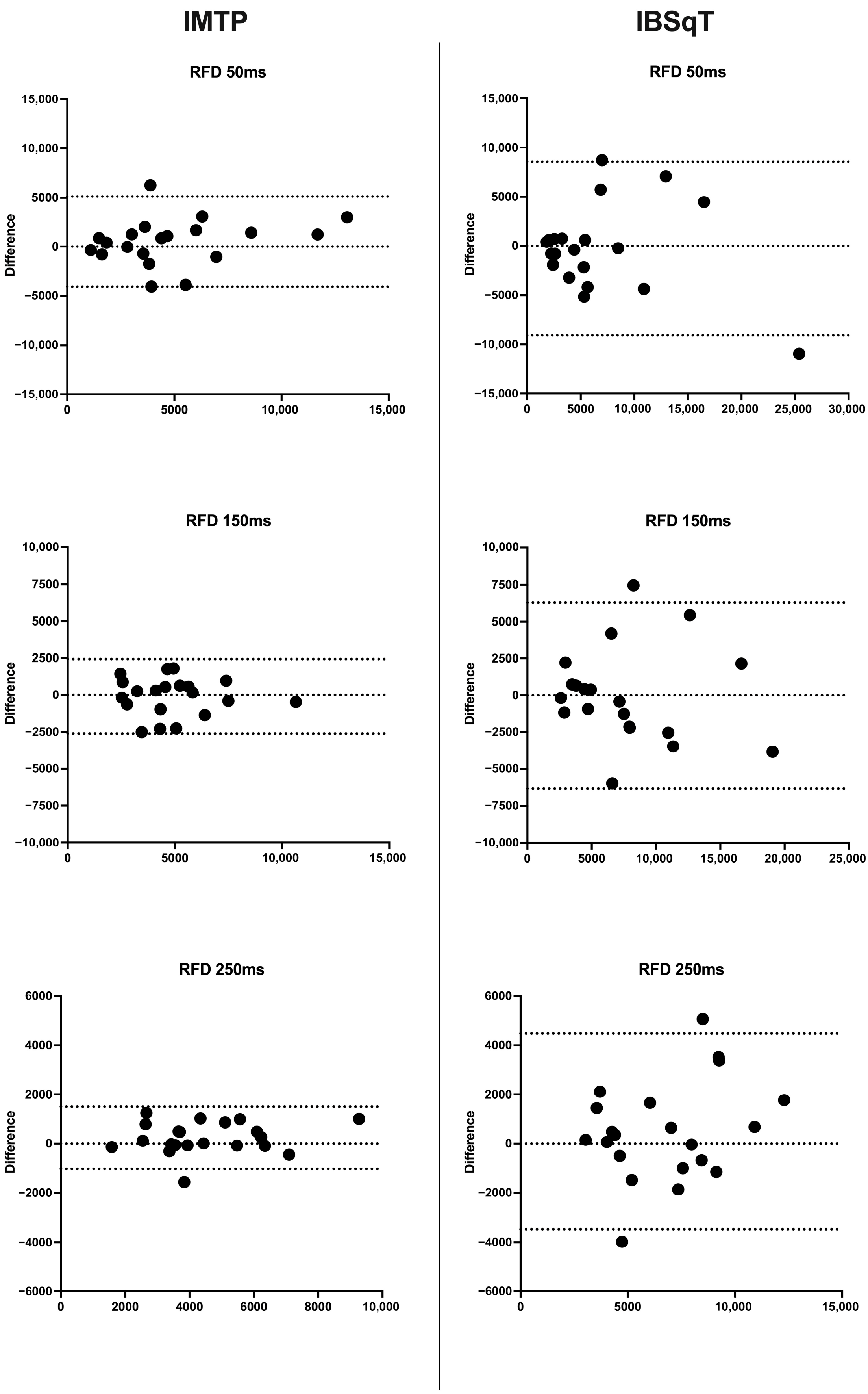

Figure 5. Bland–Altman plots of RFD at different time windows. Dashed lines represent the value of zero and the limits of agreement for the test-retest evaluations.

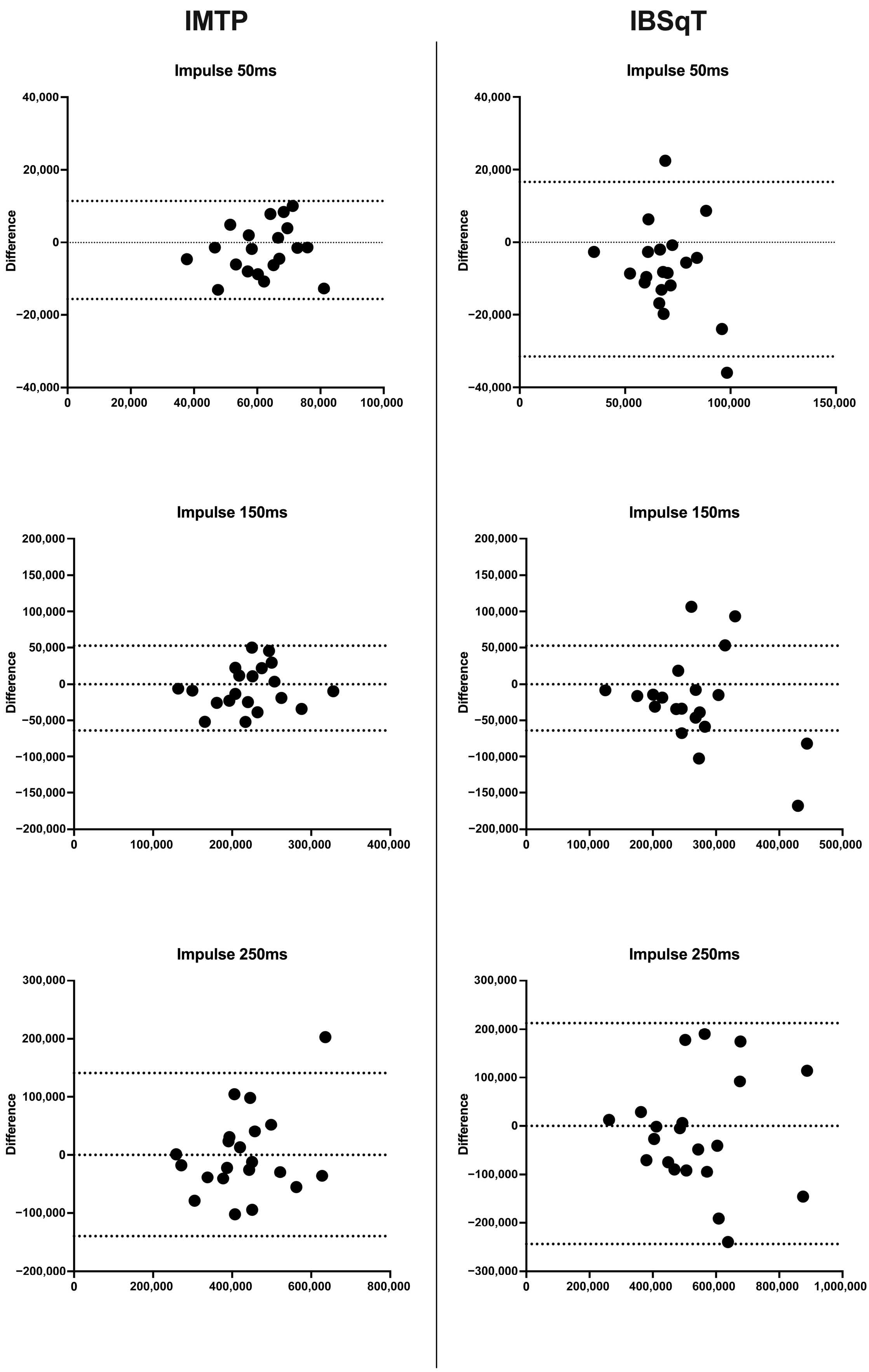

Figure 6. Bland–Altman plots of impulse at different time windows. Dashed lines represent the value of zero and the limits of agreement for the test-retest evaluations.

3.4. Between-Session Reliability in Isometric Belt Squat Test

Descriptive statistics between sessions for IBSqT, including their respective reliability tests, SEM, SWC0.2, and ES, are presented in Table 3. Like intra-session tests, PF and RPF demonstrated excellent reliability values (ICC = 0.98; 0.99) and acceptable variability (4.2–4%), with high sensitivity to performance changes in both variables. Force at all time points showed moderate to excellent reliability (ICC = 0.70; 0.90) with variability values ranging from 10.4% to 18.5% (Table 4). For RFD, ICC values range from moderate to good (0.72–0.89), with CV ranging from 21.3% to 48%. IMP across all time windows showed moderate to good reliability (ICC = 0.67–0.77), with none of the time windows meeting the acceptable variability criterion (CV = 13.7–17.7%). Paired *t*-tests revealed no significant differences between test sessions for all kinetic variables ($p > 0.05$), except for IMP 0–50 ms ($p = 0.020$; ES = 0.5 [moderate]). Additionally, RPF demonstrated good sensitivity to performance changes, as SWC0.2 scored higher than SEM. According to the Bland–Altman analysis, the average bias for peak force (PF) was −53.38 N, with a greater SD of 465.8 N and LoA between −966.3 N and 859.6 N (Figure 3). In the body mass-relative measurement (PF/BM), IBSqT showed a bias of −0.3545 N/kg, with broader LoA between −12.26 N/kg and 11.55 N/kg. For the force at 50 ms (Figure 4), IBSqT showed a higher bias of −147.7 N, with greater variability (SD = 324.6 N) and LoA between −783.9 N and 488.5 N. For the RFD at 50 ms, IBSqT showed a bias of −261 N, with LoA ranging from −9070 N to 8548 N. At 150 ms, the force showed a bias of −97.97 N, with LoA between −1090 N and 894.2 N. The RFD at 150 ms had a smaller bias of −20.82 N, but with greater variability (LoA between −6309 N and 6268 N) (Figure 5). For impulse at 150 ms, IBSqT showed a bias of −23,772 N·ms, with LoA ranging from −145,832 N·ms to 98,288 N·ms. At 250 ms, the force showed a bias of 27.6 N, with broader LoA ranging from −1153 N to 1208 N. The RFD at 250 ms showed a higher bias of 503.2 N, with LoA between −3475 N and 4481 N. For impulse at 250 ms, IBSqT demonstrated a pronounced bias of −15,658 N·ms, with even wider LoA between −244,259 N·ms and 212,943 N·ms (Figure 6).

Table 4. Between-session reliability of isometric belt squat test.

	CV% (95%CI)	ICC (95%CI)	SEM (95%CI)	SWC 0.2 (95%CI)	*p* value	ES (g) (95%CI)
Peak force (N)	6.8 (5.2–9.8)	0.94 (0.85–0.97)	351.3 (268.7–507.2)	265.4 (203.0–383.2)	0.932	−0.01 (−0.63 to 0.62)
Relative peak force (N/kg)	6.9 (5.3–10.0)	0.97 (0.92–0.99)	4.6 (3.5–6.6)	4.7 (3.6–6.7)	0.627	−0.03 (−0.65 to 0.59)
Force at 50 ms (N)	14.9 (11.4–21.5)	0.75 (0.48–0.89)	238.1 (182.2–343.9)	91.6 (70.1–132.3)	0.111	−0.26 (−0.89 to 0.36)
RFD 0–50 ms (N·s)	48.6 (37.1–70.1)	0.74 (0.47–0.89)	3243.4 (2481.4–4683.7)	1234.5 (944.4–1782.7)	0.972	0.01 (−0.62 to 0.63)
Impulse 0–50 ms (N·s)	13.2 (10.1–19.1)	0.67 (0.35–0.85)	9212.4 (7048.0–13,303.3)	3127.3 (2392.5–4516.0)	0.020	−0.05 (−1.08 to 0.18)
Force at 100 ms (N)	21.4 (16.4–30.9)	0.65 (0.31–0.84)	424.3 (324.6–612.7)	138.8 (106.2–200.5)	0.753	0.06 (−0.56 to 0.68)
RFD 0–100 ms (N·s)	27.1 (20.7–39.1)	0.89 (0.75–0.95)	2117.6 (1620.1–3058.0)	1222.9 (935.6–1765.9)	0.682	0.04 (−0.58 to 0.67)
Impulse 0–100 ms (N·s)	15.2 (11.6–22.0)	0.72 (0.43–0.88)	24,267.6 (18,566.2–35,044.1)	8909.6 (6816.4–12,866.1)	0.397	−0.14 (−0.77 to 0.48)
Force at 150 ms (N)	17.8 (13.6–25.6)	0.78 (0.54–0.91)	419.4 (320.9–605.6)	172.8 (132.2–249.5)	0.842	−0.03 (−0.65 to 0.59)
RFD 0–150 ms (N·s)	34.2 (26.2–49.4)	0.72 (0.43–0.88)	2637.3 (2017.7–3808.4)	964.5 (737.9–1392.7)	0.609	0.09 (−0.54 to 0.71)
Impulse 0–150 ms (N·s)	17.7 (13.6–25.6)	0.68 (0.36–0.86)	47,313.1 (36,197.3–68,323.4)	16,140.0 (12,348.0–23,307.3)	0.241	−0.21 (−0.84 to 0.41)

Table 4. *Cont.*

	CV% (95%CI)	ICC (95%CI)	SEM (95%CI)	SWC 0.2 (95%CI)	*p* value	ES (g) (95%CI)
Force at 200 ms (N)	15.1 (11.6–21.9)	0.81 (0.58–0.92)	403.1 (308.4–582.2)	176.0 (134.6–254.1)	0.650	−0.06 (−0.69 to 0.56)
RFD 0–200 ms (N·s)	22.3 (17.0–32.1)	0.81 (0.59–0.92)	1624.3 (1242.7–2345.6)	719.7 (550.6–1039.3)	0.447	0.11 (−0.52 to 0.73)
Impulse 0–200 ms (N·s)	16.8 (12.9–24.3)	0.75 (0.47–0.89)	66,919.3 (51,197.2–96,636.1)	25,649.7 (19,623.5–37,039.9)	0.549	−0.10 (−0.72 to 0.53)
Force at 250 ms (N)	14.7 (11.3–21.2)	0.77 (0.52–0.90)	425.8 (325.8–614.9)	171.1 (130.9–247.1)	0.836	0.03 (−0.59 to 0.66)
RFD 0–250 ms (N·s)	21.3 (16.3–30.8)	0.76 (0.50–0.90)	1435.2 (1098.0–2072.5)	564.5 (431.9–815.2)	0.269	0.17 (−0.45 to 0.80)
Impulse 0–250 ms (N·s)	15.3 (11.7–22.1)	0.77 (0.51–0.90)	83,347.7 (63,765.9–120,359.8)	33,422.8 (25,570.4–48,264.9)	0.736	−0.05 (−0.68 to 0.57)

IMTP: Isometric Mid-Thigh Pull; SD: Standard Deviation; CV%: Coefficient of Variation; ICC: Intraclass Correlation Coefficient; SEM: Standard Error of Measurement; SWC: Smallest Worthwhile Change; N: Newton; N/kg: Newton per kilogram); N·s: Newton-second.

4. Discussion

The aim of this study was to examine intra- and inter-session reliability in IMTP and IBSqT for the kinetic variables PF, RPF, and RFD at various time windows (0–50; 0–100; 0–150; 0–200; 0–250 ms), force at specific time points (50; 100; 150; 200; 250 ms), and impulse (IMP at 0–50; 0–100; 0–150; 0–200; 0–250 ms) in strength-trained individuals and report the values for SEM and SWC in both tests. The main findings of the study were: (a) absolute and relative reliability for PF and RPF in IMTP and IBSqT within the session were determined; (b) acceptable reliability for all IMP variables except IMP0–150 ms in IBSqT, while other analyzed variables were considered unreliable; and (c) excellent reliability for PF and RPF in IMTP and IBSqT between sessions, and acceptable reliability for IMP 0–50 ms and RFD 0–250 ms in IMTP between sessions. Additionally, PF and RPF are sensitive metrics for detecting performance changes in both tests.

This study demonstrated that PF and RPF within-session for both tests are reliable, with an acceptable range of variability, which is consistent with previous research [27,42,43]. Although RFD across all its time windows achieved reliability values ranging from low to excellent for IMTP and good to excellent for IBSqT, these metrics exhibited significant variability between trials, which does not ensure reproducibility within the session. Previous research has reported that RFD measures (0–200 ms) are reliable with ICC > 0.8 despite CV > 15% [27,44]. Haff et al. (2015) reported reliability for time windows ranging from 0–30 ms to 0–250 ms (ICC > 0.8 and CV < 10%), differing from the results found in this study, except for RFD 0–250 ms for IMTP, which is a reliable variable between sessions (ICC = 0.87–0.98, CV = 7.7–14.6%). The variable force at all its time points showed moderate to good reliability with CV > 10% for IMTP, and moderate to excellent with CV > 10% for IBSqT. This finding is inconsistent with Beckham et al. (2018), who reported reliability for force at 50, 90, 200, and 250 ms across various hip and knee positions (ICC = 0.95, CV 8.4%), and with Dos'Santos et al. (2017), who reported within-session reliability (ICC = 0.85–0.94, CV = 5.7–10%) and between-session reliability (ICC = 0.86–0.96, CV = 3.8–7.9%) for force (30, 50, 90, 100, 150, 200, and 250 ms). Impulse at 90 ms, 200 ms, and 250 ms has been reported as reliable for IMTP and IBSqT in previous studies [17,44], contrasting with this study where IMTP did not achieve acceptable values for IMP across all time windows, unlike IBSqT which achieved acceptable reliability within the session, except for IMP 0–150 ms.

Between-session analyses demonstrated excellent PF values for IMTP, consistent with literature reports [28,44], and good to excellent for IBSqT with no precedents in the scientific literature. RPF demonstrated good to excellent reliability for both tests with low variability between sessions. Both PF and RPF for IMTP and IBSqT are metrics that offer reliability and test-retest reproducibility. IMP 0–50 ms was found to be reliable between sessions. For RFD, only RFD 0–250 ms achieved acceptable reliability in IMTP, aligning with some studies where authors conclude that this metric is unreliable and excessively variable between sessions [44]. Reliable RFD data may require a high level of subject familiarity with such tests [45]. Another important contribution of this study is the confirmation that both IMTP and IBSqT are sensitive to performance changes. The SEM value indicates the range within which the true score of the subject in the test may fall, using the same unit of measurement as the test, and generally helps determine if there were significant performance changes [46] if this value is below the minimal detectable change (SDD); otherwise, it could be attributed to measurement error [39]. This study utilized SWC0.2, which, unlike SDD, provides information on whether the obtained value is not only significant but also clinically relevant for detecting performance changes. Coaches and sports science professionals can use SWC0.5 to provide a context of "clinically relevant change" to group analysis, as SWC0.2 may lack sensitivity [40,41]. However, when comparing the bias with previous studies, the results of this study reveal greater bias and variability in the IMTP force measurements, suggesting that factors such as technique, familiarity with the protocol, or individual participant characteristics may have influenced the higher dispersion observed. While the average bias is low and consistent with prior research, the wide limits of agreement (LoA) and the high standard deviation of the bias (224.6 N) indicate greater variability in the measurements within the conditions of this study. These findings are more pronounced when compared to studies that use highly standardized protocols, such as Comfort et al. (2015), which reported limits of agreement between −150 N and 150 N, much narrower than the ±456.9 N observed in this study. This increase in variability could be related to differences in the protocol used (e.g., execution technique or warm-up) or the sample characteristics, as this study included athletes with varying strength levels. Regarding test-retest reliability, previous research such as that of Hales et al. (2018) reported a coefficient of variation (CV) between 2 and 4% and a standard deviations of bias less than 100 N, indicating high consistency in repeated IMTP measurements. In this study, the standard deviation of the bias was considerably higher (224.6 N), which could affect the sensitivity to detect small or moderate changes in peak force. This suggests that although the IMTP is a reliable test, the higher variability observed in this study could make it more difficult to detect subtle changes in performance in trained athletes. This variability may also impact the interpretation of training program effectiveness, as current methods may not be sensitive enough to identify small or moderate strength improvements. For example, Thomas et al. (2017) reported average increases of 150–300 N in trained athletes. According to the limits of agreement in this study (±456.9 N), both tests may be too wide to distinguish these typical increases from methodological noise, highlighting the importance of having more precise and standardized protocols when closely monitoring training adaptations. In conclusion, while both IMTP and IBSqT show a low average bias and are capable of detecting changes in maximal force production, the wide limits of agreement and high variability observed in this study suggest that factors such as technique, familiarity with the protocol, and individual participant characteristics may influence the results. This increase in variability highlights the need for greater control and standardization in measurement protocols to improve the reliability and sensitivity of these tests in assessing isometric strength in trained populations. It is important to note that, for this study, the results were not divided by sex, which could reveal different parameters when interpreting results, consistent with the existing literature [24]. Another potential divergent factor could be the evaluator's learning curve with IBSqT, a test that lacks a standardized protocol. As the evaluator gains experience with the test, reliability may increase. Future research should aim to establish reliability data in elite athlete populations and explore the degree of correlation between IBSqT and athletic performance variables. A potential limitation of this study is that no sex-specific analysis was performed, as the primary objective focused on evaluating the reproducibility of maximum strength tests in general. This may slightly limit the extrapolation of the results to men and women separately, as there could be factors that influence the consistency of the tests differently based on sex. Future research could explore this variable in greater detail by including more balanced samples and conducting sex-specific analyses. Additionally, it would be valuable to examine how other variables, such as training level, prior experience, or anthropometric characteristics, might affect the reliability of these tests in diverse populations.

The results indicate that PF and RPF are highly reliable metrics for both tests, demonstrating excellent within-session and between-session reliability. These variables showed consistent performance across multiple trials, highlighting their sensitivity to performance changes, which is crucial for evaluating maximal force production in strength athletes. However, the reliability of other measured variables, such as RFD and IMP, exhibited more variability. While RFD achieved acceptable reliability in certain time windows, it showed considerable variability within and between sessions, especially in the IBSqT. This suggests that RFD may require increased test familiarity or a more standardized protocol to enhance reproducibility. Additionally, while IMP demonstrated acceptable reliability in IBSqT, it did not achieve consistent reliability across all time windows in the IMTP. These findings emphasize the importance of considering the variability of these measures, particularly in contexts where precise force production monitoring is critical. The study also revealed greater bias and variability in the IMTP force measurements compared to previous research. This could be attributed to several factors, such as differences in protocol execution, warm-up procedures, or the diverse strength levels within the participant sample. The wide limits of agreement and the high standard deviation of the bias observed in this study suggest that while the IMTP and IBSqT can detect changes in force production, the measurement variability limits their ability to detect subtle performance improvements in trained athletes. These factors underline the need for greater standardization in the execution of these tests, to enhance their sensitivity and reliability when tracking small to moderate strength changes. In conclusion, while both IMTP and IBSqT demonstrate good reliability for measuring PF and RPF, their sensitivity and ability to detect subtle changes in maximal strength may be compromised by high variability in RFD and IMP measurements. Standardizing protocols and reducing testing variability could improve the precision of these tests, making them more effective tools for tracking training adaptations and performance changes in strength-trained athletes.

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