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Abstract

Isometric tests have been used to assess rate of force development (RFD), however variation in testing methodologies are known to effect performance outcomes. The aim of this study was to assess the RFD in the isometric squat (ISqT) using two test protocols and two testing angles. Eleven participants (age: 26.8 ± 4.5 years, strength training experience: 7.1 ± 3.03 years) completed test and retest sessions one week apart, whereby two test protocols with respect to duration and instructions were compared. Isometric peak force (ISqT^{peak}) and isometric explosive force (ISqT^{exp}) tests were assessed at two joint angles (knee flexion angle 100° and 125°). Force-time traces were sampled and subsequently analysed for RFD measures. Average and instantaneous RFD variables did not meet reliability minimum criteria in ISqT^{peak} at 100° or 125°. The ISqT^{exp} test at 100° met reliability criteria in the RFD 0–200 and 0–250ms variables. The ISqT^{exp} test at 125° met reliability criteria in the RFD 0-150, 0–200 and 0–250ms variables. Force-time characteristics were optimized at the higher knee joint angle. This study provides new insights into the reliability of RFD testing. Average and instantaneous RFD measures obtained using a traditional peak force test do not meet basic reliability criteria. Researchers assessing multi-joint RFD should employ the explosive RFD test protocol as opposed to the traditional isometric peak force.

Keywords: explosive force; maximal strength; stability reliability; neuromuscular

Introduction

Movement during sports performance is characterized as multi-joint in nature whereby explosive actions are critical to performance outcomes. Therefore, it’s important to test force capacity under these conditions if researchers and coaches are to make practical decisions from assessment (Tillin, Pain, & Folland, 2013). Rate of force development (RFD) is a mechanical quantity describing the rate of a muscle-tendon contraction (Andersen, Andersen, Zebis, & Aagaard, 2010; Maffiuletti et al., 2016). Compared to isometric peak force, RFD is more strongly related to sports performance actions and activities of daily living (Maffiuletti, Bizzini, Widler, & Munzinger, 2010; Tillin et al., 2013). RFD is also more responsive in detecting acute and chronic adaptations in neuromuscular function (Crameri et al., 2007; Hornsby et al., 2017) and has been used as an indirect biological marker of acute structural damage to muscle tissue resulting from exercise (Jenkins et al., 2014; Penailillo, Blazevich, Numazawa, & Nosaka, 2015).

RFD during isometric contraction is calculated from the slope of the force-time trace (Kawamori et al., 2006; Tillin et al., 2013). Variation in methodological approaches to calculating RFD kinetics include average RFD, instantaneous RFD, and RFD using a range of preset epochs (Haff, Ruben, Lider, Twine, & Cormie, 2015) and can be described as early or late in terms of the time from contraction onset (Andersen et al., 2010). The reliability of RFD measures is also affected by the chosen variables of interest (Brady, Harrison, Flanagan, Haff, & Comyns, 2017; Dos'Santos et al., 2016; Haff et al., 2015). With respect to isometric testing, generally it is accepted that RFD is a less reliable measure than peak force during maximal voluntary contractions or peak force tests (Maffiuletti et al., 2016). Specifically, RFD assessed early in the force-time trace (within the first 150ms from contraction onset) has shown poor reliability in terms of absolute and relative reliability (Palmer, Pineda, & Durham, 2017; Prieske, Wick, & Granacher, 2014).

Work by Maffiuletti et al. (2016) detailed factors effecting isometric testing that require careful consideration such as testing angle and instruction. The appropriate implementation and analysis of RFD measures is critical to obtain both reliable and valid assessments of neuromuscular capacity (Dos'Santos, Lake, Jones, & Comfort, 2018). However, few studies have addressed the factors outlined by Halperin, Williams, Martin, and Chapman (2016); Maffiuletti et al. (2016); Rodríguez-Rosell, Pareja-Blanco, Aagaard, and González-Badillo (2018) with respect to isometric multi-joint tests. Existing literature assessing the reliability of RFD measures can be categorized as within session reliability (also termed internal consistency or between trial reliability) and stability reliability investigations (also termed test-retest or between session reliability). Stability reliability designs with appropriate time period between tests have greater ecological validity given the reliability statistics represent a time period more akin to the normal variance in assessing athletes in the field of sports science (Taylor, Cronin, Gill, Chapman, & Sheppard, 2010). As such, the absolute error measured in stability reliability accounts for inherent biological variation and random error of participants (Atkinson & Nevill, 1998; Hopkins, 2000). In simplistic terms the smaller the absolute error in stability reliability design, the better the measure (Hopkins, 2000). Surprisingly, stability reliability investigations are scarce within isometric multi-joint testing research investigating RFD (Comfort, Jones, McMahon, & Newton, 2015; Dos'Santos, Thomas, Jones, McMahon, & Comfort, 2017; Drake, Kennedy, & Wallace, 2017). Presumably this study design is implemented less frequently in sports science research as its less practical and time efficient to do so compared to within session reliability designs. Furthermore, measurement of the absolute error enables the calculation of the smallest detectible difference (Drake, Kennedy, & Wallace, 2018). Beyond this threshold, practical inferences can be made that measures in a population are ‘true’ changes beyond the error of the test.

Reliable testing equipment and protocols are needed to accurately determine responsiveness in isometric performance (Prieske et al., 2014). Based on the instructions provided, isometric contractions can be performed with two different goals: (1) to produce force as quickly as possible and maintain this force application to reach a maximal force output, (2) produce force as fast as possible, categorized as explosive contractions (Duchateau & Baudry, 2014; Tillin et al., 2013). Results comparing these types of isometric contractions have reported RFD to be 16% higher for the explosive protocol (Duchateau & Baudry, 2014). However, such contrasts have not been shown in isometric multi-joint tests. Multi-joint RFD tests have predominantly been implemented with the aim to produce a maximum peak force (evidenced in the duration of trial), with analyses of RFD characteristics occurring from the resultant force-time traces (Brady et al., 2017; Dos'Santos et al., 2017; Haff et al., 2015). Subsequently, we define this approach as the traditional isometric multi-joint peak force test. This traditional approach to instruction and duration is known to result in lower RFD values when using isometric tests (Holtermann, Roeleveld, Vereijken, & Ettema, 2007; Sahaly, Vandewalle, Driss, & Monod, 2001). Further investigation of testing protocols such as contraction durations and specific instruction as discussed above are required in isometric multi-joint tests. The primary aim of this study was to assess reliability of force-time characteristics of the isometric squat test (ISqT) using a traditional peak force protocol and an explosive force test protocol. Secondly, this study aimed to assess reliability characteristics at two knee flexion angles, 100 and 125°. Lastly this study aimed to provide normative smallest detectible difference thresholds for RFD measures using the ISqT test.

Methods

Participants

Eight male and three female participants volunteered to take part in this study (age: 26.8 ± 4.5

years, height: 1.77 ± 9.8 m, mass: 83.4 ± 9.3 kg, strength training experience: 7.1 ± 3.03 years). Participant inclusion criteria was set as requiring at least two years' strength training experience and be familiar with maximal strength testing. Ethical approval was provided by the University institutional review board (Ulster University). Prior to study commencement, all participants provided written informed consent. Procedures used within this investigation conformed to the Declaration of Helsinki.

Procedures

Testing sessions were standardized to a set time of the day for each participant to maintain consistency of circadian rhythmicity (Teo, McGuigan, & Newton, 2011). Participants were instructed to maintain their normal physical activity level and nutritional habits throughout the duration of the study. Participants were not permitted to undertake any strength, plyometric or speed training or take any ergogenic supplement throughout involvement in this study. This study assessed the stability reliability of isometric force-time characteristics. Two testing sessions (test and retest) took place one week apart, whereby participants completed isometric squat peak force ($ISqT^{peak}$) and isometric squat explosive force ($ISqT^{exp}$) tests at two relative joint angles (knee flexion angle 100° and 125°). The two test protocols were utilized with the known influence of instruction and the goal on the test on the measurement outcome (Holtermann et al., 2007; Sahaly et al., 2001). Within testing sessions participants completed $ISqT^{peak}$ and $ISqT^{exp}$ at 100°, then completed $ISqT^{peak}$ and $ISqT^{exp}$ at 125°. Prior to reliability assessments, participants undertook two familiarisation sessions following the specific testing procedures outlined below. Familiarisation sessions were used to stabilize learning effects associated with multi-joint isometric testing (Drake et al., 2018).

A standardized warm-up comprising three minutes of easy jogging followed by dynamic squatting and lunging movements was undertaken by all participants before the specific isometric warm up began. Participants then completed warm-up repetitions of the isometric squat at self-determined estimated 75% and 90% of maximal effort prior to beginning testing at the 100° angle. ISqT was assessed using a custom isometric rack (Samson Equipment Inc, NM, USA) anchored to the floor with adjustable settings to the nearest 2.5 cm of vertical displacement. The isometric rack was situated over two force plates (Kistler type 9286BA, Winterthur, Switzerland) connected to an analogue to digital converter (Kistler type 5691A1, Winterthur, Switzerland). Temporal and vertical ground reaction force (F_z) data were collected at a sampling frequency of 1000 Hz using Bioware® software (Version 5.1, Type 2812A). The force plates were zeroed whilst the participant was standing still with hands on their hips. As such, zero force was defined as the participants' bodyweight. Participants stood on the force plate with their feet approximately shoulder width apart, trunk near-vertical, with the immoveable bar placed above the posterior deltoids at the base of the neck and placed within the isometric rack. Participants relative testing positions were established before each trial, with the knee and hip joint angle confirmed using goniometry (66fit Ltd Lincolnshire, UK). Hip joint angle corresponding to the 100° knee flexion angle was 148±3° and 125° knee flexion angle was 160±3°. Participants' stance widths were monitored for consistency between trials. Using a TV screen mounted directly in front of the isometric rack, participants viewed the 'real time' force time trace, enabling participants to self-select the contraction onset by visual inspection of the steady baseline period. Each sampled raw force signal was visually inspected to confirm a steady baseline. Trials not satisfying this condition were excluded and repeated.

The ISqT^{peak} test was used with the primary goal to produce the highest force possible. Participants were informed that contraction duration would be three seconds. This is the typical duration used in isometric multi-joint tests with this goal (Drake et al., 2017). Participants maintained a minimal and steady baseline force for 1 second prior to maximal contraction using the visual feedback from the force-time trace on the TV screen, this procedure was repeated in the ISqT^{exp} test. Participants were instructed to "push against the bar as hard and as fast as possible" for three seconds. This focus of attention has been reported to optimize peak force output (Halperin et al., 2016). Two trials were completed at each joint angle, with two minutes' passive rest between trials.

The ISqT^{exp} test was used with the primary goal to produce the highest force as fast as possible (Sahaly et al., 2001). Participants were instructed to "push against the bar as fast and as hard as possible" for one second. Three trials were completed at each joint angle, with two minutes' passive rest between trials. Trials were manually discarded when a countermovement was visibly detected on the force-time trace during the pre-contraction period or the participant deemed that the trial was not representative of their true maximal explosive effort. Additionally, in the peak force test, trials were discarded if they varied by more than 250N from the previous.

Isometric force trace analysis

Vertical ground reaction force data was smoothed using a moving half-width of 12ms (Haff et al., 2015) before being analyzed for specific force-time characteristics using a custom spreadsheet. Contraction onset was determined in similar fashion to the work of (Tillin et al., 2013), using a backwards search of the rate of force-time trace slope. The last instantaneous point where the RFD trace crossed zero was defined as the start on the contraction. The peak force was identified as the highest value on the force-time trace. Time to peak force was calculated as the time from contraction onset to the instantaneous point were peak force was measured. Rate of force development was calculated as; $RFD = \frac{\Delta F}{\Delta t}$ and applied to pre-set epochs, 0–30, 0–50, 0–90, 0–100, 0–150, 0–200, and 0–250 milliseconds as well as average RFD between contraction onset and peak force. The highest instantaneous RFD was assessed during 1-millisecond (pRFD1), 2-millisecond (pRFD2), 5-millisecond (pRFD5), 10-millisecond, (pRFD10), 20-millisecond (pRFD20), 30-millisecond (pRFD30), and 50-millisecond (pRFD50) sampling windows. The variables listed above have been reported in previous studies (Brady et al., 2017; Dos'Santos et al., 2017; Haff et al., 2015). The mean of the two best trials were used for statistical analyses (Dos'Santos et al., 2017) following the removal of sampled trials furthest from the mean (Gathercole, Sporer, Stellingwerff, & Sleivert, 2015). The best trials were identified in the ISqT^{peak} test based on the maximum force obtained and for the ISqT^{exp} test the RFD 0-200ms variable was used in accordance with previous methods (McCaulley et al., 2009).

Statistical analysis

Prior to analysis, all data were visually inspected for normality. A Shapiro-Wilks test was implemented to assess the normality of the data distribution, and Levene’s test used for the assessment of the homogeneity of variance. Stability reliability of RFD measures were evaluated using the following reliability statistics and their associated 90% confidence intervals; intraclass correlation coefficients (ICC; 3,1), coefficient of variation (CV%), standard error of measurement (SEM). A paired sample *t* test was used to detect systematic bias between test-retest. Given no consensus standards exist for reliability measurements in sports science (Atkinson & Nevill, 1998), we opted for conventional thresholds for relative and absolute reliability as follows, ICC ≥ 0.70 (Morrow & Jackson, 1993) and CV ≤ 15% (Haff et al., 2015). To appropriately characterize the reliability statistics a variable was deemed reliable when the 90% confidence limits were observed within the above thresholds in line with recommendations made by Hopkins (2000); Morrow and Jackson (1993). The smallest detectible difference (SDD) was calculated to provide useful normative data in assessing performance change over time, $\boldsymbol{SDD} = 1.96 \times \sqrt{2} \times SEM$. The standard error or measurement was calculated as; $\boldsymbol{SEM} = SD \times \sqrt{1} - ICC$. A paired *t* test was used to compare outcome values between testing angle and testing protocol conditions. Tests of normality were performed using IBM SPSS Statistics 22 software (SPSS Inc., Chicago, IL, USA). A custom excel spreadsheet (Hopkins, 2002) was modified for the calculation of reliability statistics, with 90% confidence intervals reported for all measures.

Results

Paired *t* tests showed no systematic bias was present between test and retest time-points for any variable, except for average RFD in ISqT^{exp} test at the 100° angle ($p = 0.02$). The peak force variable met reliability criteria for the ISqT^{peak} at 100° (ICC = 0.96, CI = 0.88–0.98; CV% = 2.78, CI = 2.02-4.63) and 125° (ICC = 0.92, CI = 0.78–0.98; CV% = 4.98, CI = 3.61-8.33) but did not in the ISqT^{exp} test at either 100° or 125° angle. Time to peak force did not meet reliability criteria in any test protocol or angle. No average or instantaneous RFD variable met reliability criteria in ISqT^{peak} test at 100° or 125°. The ISqT^{exp} test at 100° met reliability criteria in the RFD 0–200 (ICC = 0.92, CI = 0.77–0.97; CV% = 7.00, CI = 5.06-11.78) and 0–250 variables (ICC = 0.94, CI = 0.81–0.98; CV% = 6.18, CI = 4.47-10.36). The ISqT^{exp} test at 125° met reliability criteria in the RFD 0-150 (ICC = 0.95, CI = 0.85–0.98; CV% = 5.83, CI = 4.22-9.77), 0–200 (ICC = 0.97, CI = 0.92–0.99; CV% = 4.13, CI = 2.99-6.88) and 0–250 variables (ICC = 0.94, CI = 0.82–0.98; CV% = 5.19, CI = 3.76-8.69). No instantaneous RFD variables met reliability criteria in the ISqT^{exp} test at 100° or 125°. Whilst not meeting reliability criteria, the stability reliability of instantaneous RFD variables was consistently better in the ISqT^{exp} compared to ISqT^{peak} test. The change in the mean between test-retest, ICC, CV%, SEM and

SDD, *d* and *p* values are presented for all variables in tables 1-4. Mean results for each test angle and test protocol are provided in table 5.

Peak force was optimised in the ISqT^{peak} compared to the ISqT^{exp} protocol, and in the 125° compared to the 100° angle. Statistical comparisons for the peak force variable are presented in table 6. Outcome values for RFD 200ms was optimised in the ISqT^{exp} compared to the ISqT^{peak} protocol, and in the 125° compared to the 100° angle. Statistical comparisons for the for RFD 200ms variable are presented in table 7.

Discussion

This study provides new insights into the reliability of multi-joint RFD testing. The primary finding being the reliability of RFD variables obtained using force-time data can be enhanced by subtle amendments to instruction and duration of test protocol. Isometric multi-joint RFD testing has traditionally used a peak force test protocol (also termed maximum voluntary contraction) over a 3 to 5 seconds' contraction duration (Alegre, Jiménez, Gonzalo-Orden, Martín-Acero, & Aguado, 2006; Comfort et al., 2015; Cormie, Deane, Triplett, & McBride, 2006; Dos'Santos et al., 2016; Dos'Santos et al., 2017; Haff et al., 2015; Leary et al., 2012; McGuigan, Newton, Winchester, & Nelson, 2010; McGuigan, Winchester, & Erickson, 2006; Thomas, Comfort, Chiang, & Jones, 2015; Thomas, Jones, Rothwell, Chiang, & Comfort, 2015). We offer evidence that the reliability of RFD is best assessed using an explosive protocol (detailed in methods section). Adopting this protocol enhances the reliability of common RFD measures in comparison to the isometric peak force test (see tables 1, 2, 3 and 4). We contend that several RFD measures demonstrate good relative and absolute reliability in the explosive force test. This finding is promising given the low participant numbers within our study effects the precision of the confidence intervals of measures (Baumgartner & Chung, 2001; Morrow & Jackson, 1993). As such we recommend the explosive force protocol be adopted in future investigations of RFD using isometric multi-joint tests.

An abundance of literature reports multi-joint RFD measures to be reliable (Comfort et al., 2015; Dos'Santos et al., 2016; Dos'Santos et al., 2017; Haff et al., 2015; Palmer et al., 2017; Thomas, Comfort, et al., 2015; Thomas, Jones, et al., 2015). For comparison between previous studies and our findings, we will discuss the absolute reliability of these studies assessing multi-joint RFD using the confidence intervals of the coefficient of variation statistic (Hopkins, 2000). In examination of reliability studies, measures of instantaneous RFD can be observed as having CI between 12 to 21% (Thomas, Jones, et al., 2015) and 8 to 17% (Thomas, Comfort, et al., 2015). Studies by Brady et al. (2017); Haff et al. (2015) present CI for a range of average and instantaneous RFD measures which extend beyond the acceptable thresholds set within their study and outside the thresholds set in our study. These studies conducted reliability assessments using between trials design, which is a limitation in terms of their usefulness. Stability reliability assessment are scarce within the published literature to date. In a study by Dos'Santos et al. (2017) showed the stability reliability statistics for average RFD 150ms had CI ranging from 6 to 21%. Other studies assessing stability reliability include (Comfort et al., 2015; Palmer et al., 2017), but these studies did not present CI thus inhibiting comparisons. In stating the CI of RFD measures of the studies above, at best the reliability of RFD measures using the traditional isometric peak force test could be described as questionable. Authors rely on presenting their sample mean CV as being within their pre-determined threshold for acceptable reliability. This method does not reflect the error across the sample of participants but only for the ‘average participant’ (Atkinson & Nevill, 1998). Given a proportion of participant’s individual reliability data will lie well outside the pre-determined ‘acceptable reliability’ thresholds. It is therefore important to characterize the true reliability as the confidence intervals of the error (Hopkins, 2000; Morrow & Jackson, 1993). Within this study, our findings show (CI of RFD measures) average and instantaneous RFD measures obtained using a traditional isometric peak force test do not meet basic reliability criteria (CI within ICC ≥ 0.70 and CV ≤ 15% thresholds). With awareness that no one statistic can demonstrate conclusiveness, it's important to provide a comprehensive approach to the assessment of reliability measures to give a 'true' picture (Bruton, Conway, & Holgate, 2000). We do not intend to present a case that any one study is reliable or not, but that issues around overall reliability of RFD measures is prevalent within existing evidence. Enhancing reliability of measures can be achieved through a rigorous approach to methodology (Maffiuletti et al., 2016) and will likely result in more informed decision making. Our study shows by amending isometric multi-joint test protocol to an explosive RFD test improves reliability of the key measures and therefore enhances their application in practice.

Whilst a multitude of variables have been assessed in multi-joint RFD tests (Brady et al., 2017; Dos'Santos et al., 2016; Haff et al., 2015; Palmer et al., 2017), it is common that researchers will decide to use a limited number of variables within their investigations for practical reasons. As such specific knowledge on the most reliable variables is required. This study provides new information by comparing the reliability of multi-joint RFD variables using an explosive isometric test. Average RFD measures <150ms post contraction onset did not meet reliability criteria. Whilst our findings are not directly comparable to other work given our reliability thresholds were more stringent, there is congruence with reports that early RFD variables (<150ms) are less reliable than RFD variables determined later (>150ms) in the force-time trace (Brady et al., 2017; Palmer et al., 2017; Prieske et al., 2014). In conjunction with the findings of Haff et al. (2015) we found the average RFD variable did not meet reliability criteria. We suggest this variable is affected by variance in contraction duration and should be avoided as a measure using the protocols implemented in our investigation. Reliability statistics for the time to peak force variable within our study across both test protocols and both test angles verify the lack of stability of contraction duration in isometric testing. Average measures over the force time trace undoubtedly provide a more comprehensive analysis of neuromuscular capacity than a single measure (Maffiuletti et al., 2016). Perhaps late RFD variables should be used instead of the overall average RFD variable as they offer greater stability reliability. We also caution the use of early RFD measures given the poor reliability found in both the isometric peak force and explosive force test in this study.

Common use of instantaneous RFD variables (also termed peak or maximum RFD) are present within sports science literature (Alegre et al., 2006; Kawamori et al., 2006; McGuigan et al., 2010; McGuigan et al., 2006; Stone et al., 2004; Stone et al., 2005; Thomas, Comfort, et al., 2015). Contrary to common use of instantaneous RFD variables in research, all instantaneous RFD measures failed to meet reliability within our study. Haff et al. (2015) reported only instantaneous RFD using a 20ms epoch was reliable, having assessed 2,5,10,20,30, and 50ms epochs. Our findings are supported by Brady et al. (2017) who showed no instantaneous measures of RFD to meet reliability criteria having used the same epochs as Haff et al. (2015) within an isometric peak force test. Maffiuletti et al. (2016) explains instantaneous RFD represents single steepest part of the force-time trace and by nature can be an inconsistent point on the force-time trace. Whilst the band-width of the epochs may accommodate the overall reliability, the measure is still inconsistent between trials and participants. Our study repeated the same epochs (Brady et al., 2017; Haff et al., 2015) and found no instantaneous variable to be reliable for the isometric explosive or peak force test. We suggest the application of instantaneous variables may be problematic using existing protocols and further work may be required to explore the function of instantaneous variables in future investigations (Maffiuletti et al., 2016).

There is considerable debate concerning the appropriate testing angle for isometric multi-joint testing. Whilst certain authors detail the importance of angle on reliability statistics (Dos'Santos et al., 2017; Palmer et al., 2017) alternative findings suggest that test angle has little effect on reliability (Comfort et al., 2015). Principally within our investigation, joint angle had negligible effects on the reliability of isometric force-time measures. However, we note a tendency for the isometric explosive force test at 125° to have greater relative and absolute reliability for average RFD measures in both the isometric peak force and isometric explosive force test compared to the 100° angle. Additionally, using the isometric explosive test the RFD 150ms variable met the overall reliability criteria for the 125° but not the 100° angle. Whilst marginal, these findings are supported by the position related increases in the reliability of isometric squats as knee flexion angle decreases in the work of Palmer et al. (2017). Rationale for this tendency is not clear, but a potential explanation for lower testing positions (higher knee and hip flexion) having marginally less reliability may be due to the greater relative muscular effort (Bryanton, Kennedy, Carey, & Chiu, 2012; Palmer et al., 2017) which in turn causes greater variation in early RFD. Given no consensus can be determined for the best isometric multi-joint testing test angle (Dos'Santos et al., 2017), we contend that arguments for the specificity of training stimulus (Balshaw, Massey, Maden-Wilkinson, Tillin, & Folland, 2016; Folland & Williams, 2007; Tillin & Folland, 2014) be considered similarly to isometric testing methodology in terms of selection of the most appropriate testing angle and protocol. For example, the study by Beckham (2012) evaluated isometric strength across a range of positions specific to participants sporting demands. This type of approach, i.e. specificity of testing angle may enhance the ability of isometric tests to detect training adaptations.

As discussed within the methodological review by Rodríguez-Rosell et al. (2018), it is often recommended that joint angles during isometric testing should be the position that optimises the mechanical output of force characteristics. Our findings confirm that peak force is optimised at the 125° knee joint angle using the isometric peak force test (see table 6). RFD 200ms values are optimised using the explosive force test comparatively to the peak force test with findings also confirming higher values at the higher angle (table 7). Taken together, we provide evidence for isometric testing at higher knee joint angles. However, we add an important finding that if testing is to be conducted under the conditions that optimise outcome variables then RFD should be assessed using the explosive force protocol implemented in this study, whereas peak force should be assessed using the traditional peak force protocol.

With appropriate stability reliability study designs, test data can be used as normative for the investigated population. For a test to be deemed useful, the smallest detectible difference should be calculated to evaluate responsiveness of training interventions in studies with comparable populations (Drake et al., 2018). Acute and chronic responses of individuals or groups beyond the SDD can thus be monitored, with changes being attributed to fatigue or adaptation rather than error in testing methodology (Dos'Santos et al., 2017; Prieske et al., 2014). The usefulness of previous work is limited by the fact that the study design assesses only between trial variation (Brady et al., 2017; Haff et al., 2015). This study provides new SDD data for the isometric explosive force test which can now be used to assess adaptation to training with comparable populations. Specific SDD for all force-time variables are provided within tables (1 and 2 for isometric peak force test at 100° and 125° respectively, 3 and 4 for isometric explosive force test at 100° and 125° respectively).

In summary, evidence from our study demonstrates enhanced reliability when assessing RFD using the isometric explosive force test compared to the traditional isometric peak force test. Principally average RFD over 150, 200 and 250ms demonstrate best reliability when using the isometric explosive force test and are recommended variables when assessing RFD. Testing angle had limited effect on reliability statistics, subsequently testing angle may be a factor more relevant to specificity in detecting adaptation as opposed to reliability investigations. Higher testing angles optimized both peak force and RFD outcomes and therefore should be considered the most appropriate angle to conduct isometric squat tests. Finally, the SDD of RFD measures provided within this study are a useful point from which responsiveness may be determined in future studies assessing RFD.

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Table 1

Table 1. Reliability statistics for $\text{ISqT}^{\text{peak}}$ test at 100° knee flexion

	Change in mean (90% CI)	ICC (90% CI)	CV% (90% CI)	SEM (90% CI)	SDD	*d*	*p*
Peak Force	3.39 (-42.67, 49.44)	0.96 (0.89, 0.99)	2.79 (2.03, 4.63)	48.15 (28.91, 67.38)	133.5	0.01	0.90
TTPF	0.11 (-0.17, 0.38)	0.44 (-0.10, 0.78)	22.27 (15.80, 39.21)	0.32 (-1.25, 1.89)	0.89	0.39	0.50
RFD 0-30ms	-60.14 (-378.2, 257.9)	0.52 (0.00, 0.82)	43.71 (30.28, 81.59)	366.9 (313.8, 420.0)	1017	-0.17	0.74
RFD 0-50ms	-243.6 (-870.4, 383.1)	0.38 (-0.18, 0.75)	67.34 (45.58, 133.3)	739.7 (664.3, 815.1)	2050	-0.45	0.49
RFD 0-90ms	-495.4 (-1726, 735.2)	0.20 (-0.36, 0.65)	89.14 (59.18, 185.3)	1479 (1372, 1586)	4100	-0.72	0.48
RFD 0-100ms	-518.7 (-1803, 765.8)	0.18 (-0.37, 0.64)	86.49 (57.55, 178.8)	1545 (1436, 1654)	4284	-0.75	0.48
RFD 0-150ms	-509.4 (-1748, 729.1)	0.25 (-0.31, 0.68)	63.09 (42.87, 123.6)	1482 (1375, 1588)	4107	-0.64	0.47
RFD 0-200ms	-390.5 (-1391, 610.1)	0.39 (-0.16, 0.76)	41.12 (28.56, 76.24)	1174 (1079, 1269)	3255	-0.44	0.49
RFD 0-250ms	-305.9 (-966.7, 354.8)	0.63 (0.17, 0.87)	25.21 (17.82, 44.77)	747.4 (671.6, 823.2)	2072	-0.32	0.42
Average RFD	-56.70 (-239.5, 126.1)	0.62 (0.15, 0.86)	23.81 (16.86, 42.10)	208.3 (168.3, 248.4)	578	-0.22	0.58
pRFD 1ms	-615.5 (-1521, 289.6)	0.69 (0.26, 0.89)	16.56 (11.82, 28.66)	1019 (930.8, 1108)	2825	-0.43	0.24
pRFD 2ms	-583.6 (-1493, 326.0)	0.68 (0.24, 0.89)	17.30 (12.34, 30.02)	1025 (936.5, 1114)	2842	-0.41	0.27
pRFD 5ms	-527.6 (-1415, 360.2)	0.69 (0.26, 0.89)	17.17 (12.25, 29.79)	998.4 (910.8, 1086)	2767	-0.37	0.30
pRFD 10ms	-560.5 (-1456, 334.9)	0.68 (0.24, 0.89)	17.60 (12.55, 30.56)	1009 (921.0, 1097)	2797	-0.40	0.28
pRFD 20ms	-590.0 (-1472, 292.0)	0.68 (0.24, 0.89)	17.81 (12.70, 30.95)	994.0 (906.6, 1081)	2755	-0.43	0.25
pRFD 30ms	-588.1 (-1456, 279.4)	0.67 (0.24, 0.88)	17.97 (12.81, 31.25)	978.3 (891.6, 1065)	2712	-0.44	0.25
pRFD 50ms	-590.9 (-1438, 256.4)	0.65 (0.20, 0.88)	18.45 (13.14, 32.12)	959.3 (873.4, 1045)	2659	-0.47	0.23

Abbreviations: ICC = intraclass correlation coefficient; CV% = coefficient of variation; SEM = standard error of measurement; SDD = smallest detectible difference; CI = confidence interval; TTPF = time to peak force (ms);

pRFD = instantaneous RFD. Peak force measured in newtons (N), RFD measured in N/s. Numerical values presented after RFD represent pre-set time epochs.

Table 2

Table 2. Reliability statistics for $\text{ISqT}^{\text{peak}}$ test at 125° knee flexion

	Change in mean (90% CI)	ICC (90% CI)	CV% (90% CI)	SEM (90% CI)	SDD	*d*	*p*
Peak Force	-30.14 (-136.8, 76.47)	0.92 (0.78, 0.98)	4.98 (3.61, 8.33)	113.1 (83.6, 142.6)	313.4	-0.08	0.62
TTPF	-0.005 (-0.24, 0.23)	0.07 (-0.47, 0.57)	15.41 (11.02, 26.59)	0.29 (-1.20, 1.77)	0.794	-0.07	0.97
RFD 0-30ms	-499.8 (-1271, 271.1)	0.22 (-0.34, 0.66)	64.27 (43.62, 126.27)	899.0 (815.9, 982.1)	2492	-1.10	0.27
RFD 0-50ms	-781.8 (-2065, 501.5)	0.34 (-0.22, 0.73)	58.40 (39.86, 113.1)	1451 (1346, 1557)	4023	-0.77	0.29
RFD 0-90ms	-766.9 (-2124, 590.7)	0.55 (0.05, 0.83)	38.46 (26.79, 70.81)	1521 (1413, 1630)	4217	-0.46	0.33
RFD 0-100ms	-719.2 (-2004, 565.1)	0.58 (0.09, 0.85)	35.44 (24.76, 64.72)	1439 (1334, 1544)	3988	-0.43	0.33
RFD 0-150ms	-695.2 (-1904, 513.5)	0.61 (0.13, 0.86)	29.70 (20.89, 53.39)	1351 (1249, 1453)	3744	-0.42	0.32
RFD 0-200ms	-563.2 (-1570, 444.0)	0.68 (0.25, 0.89)	25.02 (17.69, 44.40)	1114 (1022, 1207)	3088	-0.35	0.33
RFD 0-250ms	-300.8 (-1036, 434.3)	0.77 (0.41, 0.92)	19.91 (14.16, 34.81)	805 (726, 883)	2230	-0.21	0.47
Average RFD	-19.0 (-174, 136.2)	0.31 (-0.25, 0.72)	16.31 (11.65, 28.22)	184 (146, 221)	509.3	-0.16	0.83
pRFD 1ms	-1187 (-2957, 583.6)	0.62 (0.15, 0.86)	23.32 (16.52, 41.17)	1955 (1832, 2077)	5418	-0.48	0.25
pRFD 2ms	-1148 (-2923, 627.8)	0.63 (0.16, 0.87)	24.39 (17.25, 43.19)	1961 (1838, 2083)	5435	-0.46	0.27
pRFD 5ms	-1110 (-2872, 652.1)	0.64 (0.17, 0.87)	24.65 (17.43, 43.69)	1947 (1824, 2069)	5396	-0.44	0.28
pRFD 10ms	-1127 (-2905, 651.7)	0.63 (0.16, 0.87)	25.22 (17.83, 44.78)	1969 (1846, 2092)	5457	-0.45	0.28
pRFD 20ms	-1099 (-2828, 630.5)	0.63 (0.17, 0.87)	24.96 (17.65, 44.29)	1916 (1794, 2037)	5310	-0.44	0.27
pRFD 30ms	-1029 (-2686, 627.8)	0.64 (0.18, 0.87)	24.53 (17.35, 43.47)	1837 (1719, 1956)	5093	-0.43	0.28
pRFD 50ms	-853.3 (-2345, 638.6)	0.65 (0.20, 0.88)	23.57 (16.69, 41.65)	1661 (1548, 1774)	4605	-0.38	0.32

Abbreviations: ICC = intraclass correlation coefficient; CV% = coefficient of variation; SEM = standard error of measurement; SDD = smallest detectible difference; CI = confidence interval; TTPF = time to peak force (ms);

pRFD = instantaneous RFD. Peak force measured in newtons (N), RFD measured in N/s. Numerical values presented after RFD represent pre-set time epochs.

Table 3

Table 3. Reliability statistics for ISqT^{exp} test at 100° knee flexion

	Change in mean (90% CI)	ICC (90% CI)	CV% (90% CI)	SEM (90% CI)	SDD	*d*	*p*
Peak Force	-106.4 (-212.6, -0.30)	0.87 (0.63, 0.96)	8.53 (6.15, 14.41)	114.4 (84.71, 144.0)	317.0	-0.37	0.10
TTPF	0.029 (-0.020, 0.079)	0.86 (0.63, 0.96)	11.25 (8.08, 19.17)	0.053 (-0.586, 0.693)	0.148	0.22	0.30
RFD 0-30ms	-296.6 (-821.5, 228.3)	0.63 (0.16, 0.87)	65.94 (44.68, 130.1)	593.2 (525.7, 660.7)	1644	-0.40	0.33
RFD 0-50ms	-632.5 (-1585, 320.0)	0.67 (0.23, 0.88)	51.13 (35.15, 97.28)	1072 (981.0, 1162)	2971	-0.43	0.25
RFD 0-90ms	-706.5 (-1713, 299.8)	0.65 (0.20, 0.88)	24.42 (17.28, 43.25)	1134 (1040, 1227)	3143	-0.47	0.23
RFD 0-100ms	-632.0 (-1535, 271.3)	0.67 (0.23, 0.88)	21.68 (15.39, 38.11)	1009 (920.8, 1097)	2796	-0.45	0.23
RFD 0-150ms	-420.2 (-930.6, 90.3)	0.83 (0.55, 0.94)	11.51 (8.27, 19.63)	549.9 (484.9, 615.0)	1524	-0.35	0.17
RFD 0-200ms	-260.3 (-566.0, 45.4)	0.92 (0.77, 0.97)	7.00 (5.06, 11.78)	323.2 (273.4, 373.1)	895.9	-0.24	0.15
RFD 0-250ms	-246.6 (-484.3, -9.0)	0.94 (0.81, 0.98)	6.18 (4.47, 10.36)	249.8 (206.0, 293.6)	692.5	-0.26	0.09
Average RFD	-368.4 (-601.9, -134.9)	0.93 (0.80, 0.98)	10.48 (7.54, 17.82)	247.1 (203.5, 290.6)	684.8	-0.41	0.02
pRFD 1ms	4.66 (-944.9, 954.2)	0.85 (0.59, 0.95)	10.54 (7.58, 17.92)	1023 (934.1, 1111)	2835	0.00	0.99
pRFD 2ms	-32.66 (-1013, 947.9)	0.84 (0.57, 0.95)	11.04 (7.94, 18.81)	1056 (966.2, 1146)	2928	-0.01	0.95
pRFD 5ms	51.30 (-955.4, 1058)	0.84 (0.56, 0.95)	11.59 (8.33, 19.78)	1085 (993.8, 1176)	3008	0.02	0.93
pRFD 10ms	25.75 (-976.5, 1028)	0.84 (0.56, 0.95)	11.67 (8.38, 19.91)	1080 (988.9, 1171)	2994	0.01	0.96
pRFD 20ms	23.74 (-962.2, 1010)	0.83 (0.55, 0.94)	11.75 (8.44, 20.05)	1063 (972.3, 1153)	2946	0.01	0.97
pRFD 30ms	17.47 (-932.1, 967.0)	0.83 (0.54, 0.94)	11.61 (8.34, 19.81)	1024 (935.2, 1113)	2838	0.01	0.97
pRFD 50ms	21.12 (-823.9, 866.1)	0.82 (0.52, 0.94)	11.08 (7.97, 18.87)	910.3 (826.6, 993.9)	2523	0.01	0.96

Abbreviations: ICC = intraclass correlation coefficient; CV% = coefficient of variation; SEM = standard error of measurement; SDD = smallest detectible difference; CI = confidence interval; TTPF = time to peak force (ms);

pRFD = instantaneous RFD. Peak force measured in newtons (N), RFD measured in N/s. Numerical values presented after RFD represent pre-set time epochs.

Table 4

Table 4. Reliability statistics for ISqT^{exp} test at 125° knee flexion

	Change in mean (90% CI)	ICC (90% CI)	CV% (90% CI)	SEM (90% CI)	SDD	*d*	*p*
Peak Force	-102.4 (-241.5, 36.77)	0.79 (0.46, 0.93)	7.29 (5.26, 12.27)	152.7 (118.4, 186.9)	423.2	-0.35	0.21
TTPF	-0.080 (-0.150, -0.011)	0.74 (0.36, 0.91)	23.96 (16.96, 42.39)	0.077 (-0.694, 0.849)	0.215	-0.63	0.06
RFD 0-30ms	-168.0 (-692.8, 356.7)	0.63 (0.17, 0.87)	34.50 (24.13, 62.84)	594.1 (526.6, 661.7)	1647	-0.22	0.57
RFD 0-50ms	-395.1 (-1200, 409.4)	0.77 (0.42, 0.92)	28.28 (19.92, 50.64)	888.4 (805.8, 971.0)	2463	-0.25	0.39
RFD 0-90ms	-540.3 (-1199, 117.9)	0.90 (0.71, 0.97)	13.00 (9.32, 22.27)	703.5 (630.0, 777.0)	1950	-0.26	0.17
RFD 0-100ms	-491.2 (-1071, 88.36)	0.91 (0.75, 0.97)	10.68 (7.68, 18.17)	616.0 (547.2, 684.8)	1707	-0.25	0.15
RFD 0-150ms	-421.0 (-816.6, -25.47)	0.95 (0.85, 0.98)	5.83 (4.22, 9.77)	414.7 (358.2, 471.1)	1149	-0.23	0.08
RFD 0-200ms	-298.2 (-547.0, -49.45)	0.97 (0.92, 0.99)	4.13 (3.00, 6.88)	259.1 (214.5, 303.7)	718.2	-0.19	0.056
RFD 0-250ms	-338.6 (-645.6, -31.61)	0.94 (0.82, 0.98)	5.20 (3.76, 8.69)	323.6 (273.7, 373.5)	896.9	-0.27	0.07
Average RFD	795.8 (-215.8, 1807)	0.60 (0.11, 0.85)	22.48 (15.94, 39.60)	1125 (1032, 1218)	3119	0.59	0.18
pRFD 1ms	51.51 (-936.1, 1039)	0.91 (0.74, 0.97)	10.09 (7.26, 17.13)	1052 (962.2, 1142)	2916	0.02	0.93
pRFD 2ms	73.02 (-900.5, 1047)	0.91 (0.75, 0.97)	10.05 (7.24, 17.07)	1036 (946.5, 1125)	2871	0.02	0.89
pRFD 5ms	90.58 (-940.1, 1121)	0.91 (0.73, 0.97)	11.08 (7.97, 18.87)	1099 (1007, 1191)	3047	0.03	0.88
pRFD 10ms	37.24 (-1003, 1078)	0.90 (0.72, 0.97)	11.29 (8.11, 19.24)	1111 (1019, 1204)	3080	0.01	0.95
pRFD 20ms	30.41 (-981.3, 1042)	0.90 (0.72, 0.97)	11.11 (7.99, 18.93)	1081 (989.6, 1172)	2996	0.01	0.96
pRFD 30ms	8.05 (-949.1, 965.2)	0.90 (0.71, 0.97)	10.75 (7.73, 18.29)	1023 (934.0, 1111)	2835	0.00	0.99
pRFD 50ms	-43.52 (-859.5, 772.4)	0.90 (0.71, 0.97)	9.66 (6.95, 16.38)	871.4 (789.5, 953.2)	2415	-0.02	0.92

Abbreviations: ICC = intraclass correlation coefficient; CV% = coefficient of variation; SEM = standard error of measurement; SDD = smallest detectible difference; CI = confidence interval; TTPF = time to peak force (ms);

pRFD = instantaneous RFD. Peak force measured in newtons (N), RFD measured in N/s. Numerical values presented after RFD represent pre-set time epochs.

Table 5. Mean results by test protocol and test angle

	ISqT^{peak} 100 (Mean ± SD)	ISqT^{peak} 125 (Mean ± SD)	ISqT^{exp} 100 (Mean ± SD)	ISqT^{exp} 125 (Mean ± SD)
Peak Force	2013 ± 251.7	2904 ± 408.8	1791 ± 315.5	2393 ± 337.0
TTPF	1.78 ± 0.43	2.03 ± 0.30	0.53 ± 0.14	0.51 ± 0.16
RFD 0-30ms	1261 ± 529	1787 ± 1015	1834 ± 974.1	2467 ± 1010
RFD 0-50ms	1950 ± 937.6	2829 ± 1781	3500 ± 1876	4549 ± 1974
RFD 0-90ms	3122 ± 1652	4349 ± 2279	5824 ± 1921	6963 ± 2241
RFD 0-100ms	3315 ± 1711	4581 ± 2229	6059 ± 1762	7192 ± 2112
RFD 0-150ms	3890 ± 1709	5548 ± 2165	6445 ± 1352	7964 ± 1867
RFD 0-200ms	3982 ± 1506	5833 ± 1980	6119 ± 1145	7831 ± 1616
RFD 0-250ms	3828 ± 1237	5577 ± 1662	5551 ± 984	7276 ± 1342
Average RFD	1034 ± 337.8	1302 ± 221.3	3360 ± 939.5	5103 ± 1870
pRFD 1ms	7068 ± 1819	9422 ± 3190	11420 ± 2626	13024 ± 3401
pRFD 2ms	6875 ± 1808	9244 ± 3223	11250 ± 2657	12817 ± 3425
pRFD 5ms	6664 ± 1784	9008 ± 3228	11030 ± 2680	12594 ± 3467
pRFD 10ms	6580 ± 1774	8934 ± 3223	10937 ± 2671	12494 ± 3432
pRFD 20ms	6479 ± 1748	8815 ± 3169	10757 ± 2591	12287 ± 3313
pRFD 30ms	6377 ± 1713	8667 ± 3068	10495 ± 2462	11994 ± 3109
pRFD 50ms	6171 ± 1630	8316 ± 2826	9844 ± 2134	11266 ± 2617

Abbreviations: TTPF = time to peak force (ms); pRFD = instantaneous RFD. Peak force measured in newtons (N), RFD measured in N/s. Numerical values presented after RFD represent pre-set time epochs.

Table 6

Table 6. Comparison of peak force values between test angle and test protocol.

	Mean difference	95% confidence interval of the difference		*p* value	Effect size	95% confidence interval of the effect	
		Lower	Upper			Lower	Upper
ISqT^{peak} 100 to ISqT^{peak} 125	-907.9	-1213	-602.6	.000	-2.20	-3.75	-1.38
ISqT^{exp} 100 to ISqT^{exp} 125	-633.1	-875.9	-390.2	.000	-1.75	-2.78	-0.72
ISqT^{peak} 100 to ISqT^{exp} 100	167.4	23.67	311.1	.027	0.50	-0.34	1.44
ISqT^{peak} 125 to ISqT^{exp} 125	442.2	254.2	630.2	.000	1.22	-0.68	1.08

Table 7. Comparison of RFD 200ms values between test angle and test protocol.

	Mean difference	95% confidence interval of the difference		*p* value	Effect size	95% confidence interval of the effect	
		Lower	Upper			Lower	Upper
ISqT^{peak} 100 to ISqT^{peak} 125	-1937	-3086	-787.6	.004	-0.82	-1.89	-0.03
ISqT^{exp} 100 to ISqT^{exp} 125	-1880	-2653	-1108	.000	-1.21	-2.34	-0.39
ISqT^{peak} 100 to ISqT^{exp} 100	-2072	-3120	-1024	.002	-1.99	-2.64	-0.62
ISqT^{peak} 125 to ISqT^{exp} 125	-2015	-3365	-666.3	.008	-1.30	-1.89	-0.04

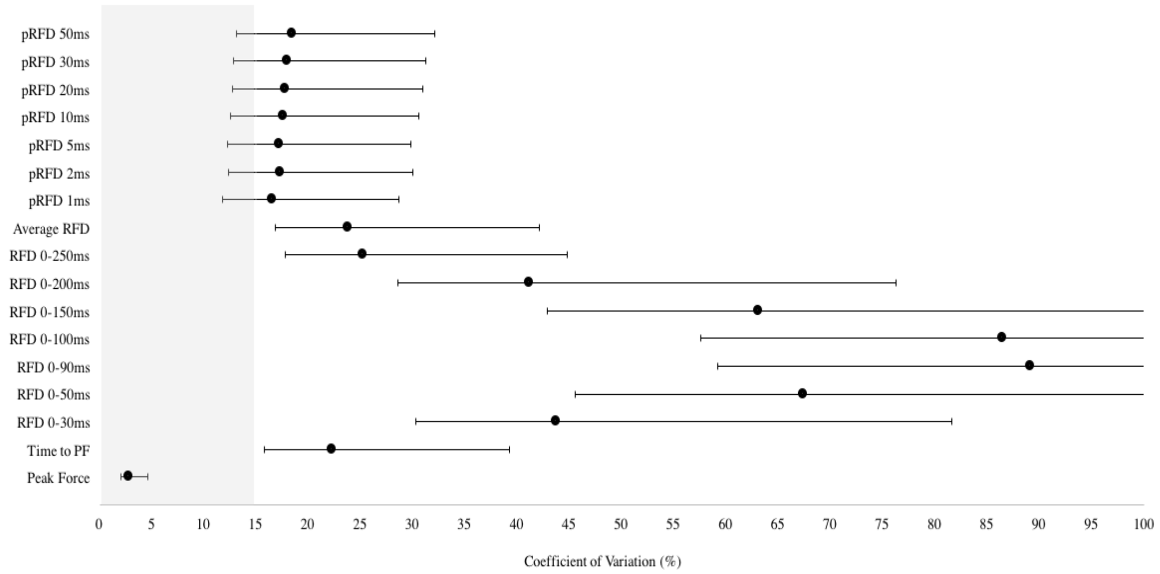

Figure 1. Coefficient of variation and 90% CI for the isometric peak force test at 100°

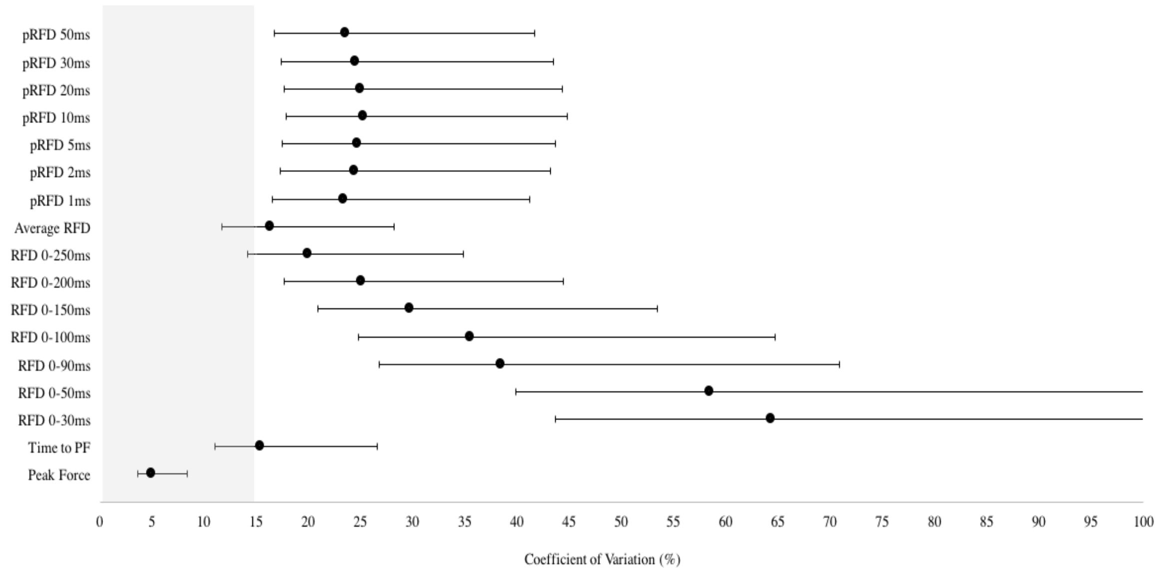

Figure 2. Coefficient of variation and 90% CI for the isometric peak force test at 125°

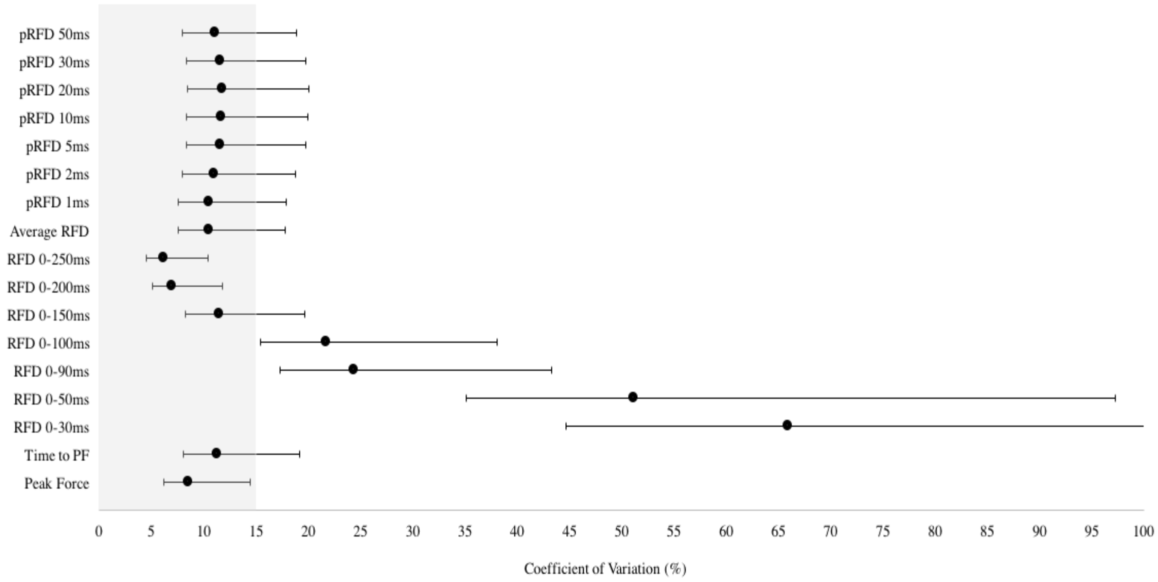

Figure 3. Coefficient of variation and 90% CI for the isometric explosive force test at 100°

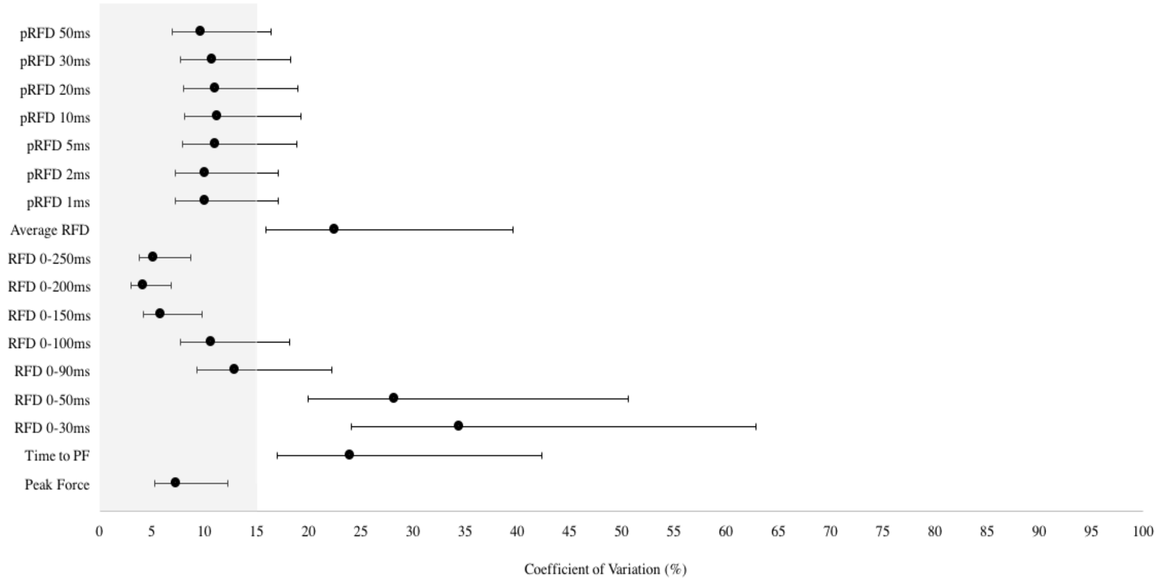

Figure 4. Coefficient of variation and 90% CI for the isometric explosive force test at 125°

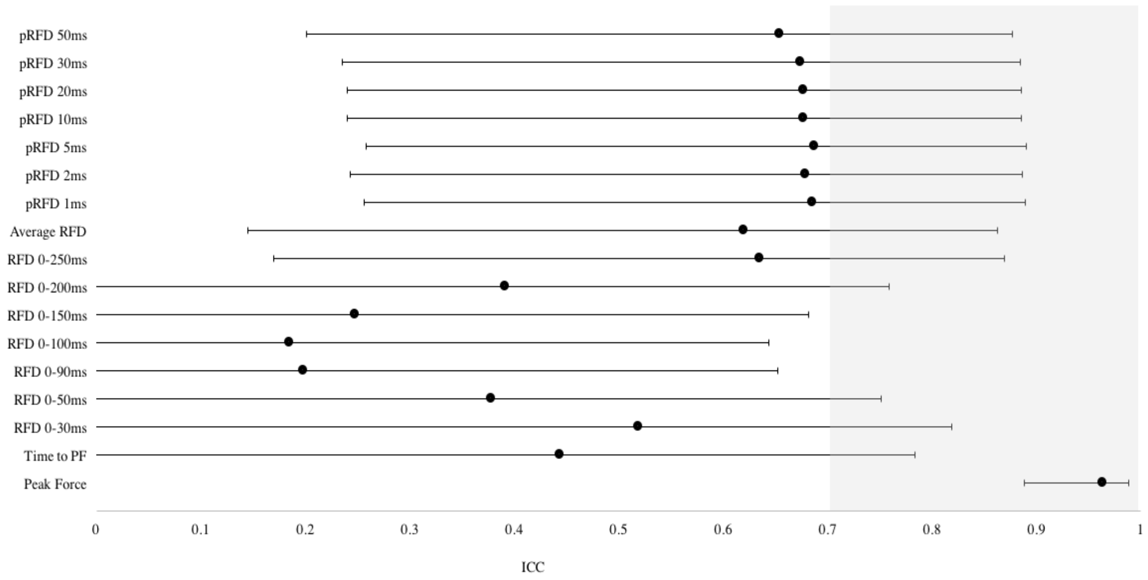

Figure 5. Intraclass coefficient and 90% CI for the isometric peak force test at 100°

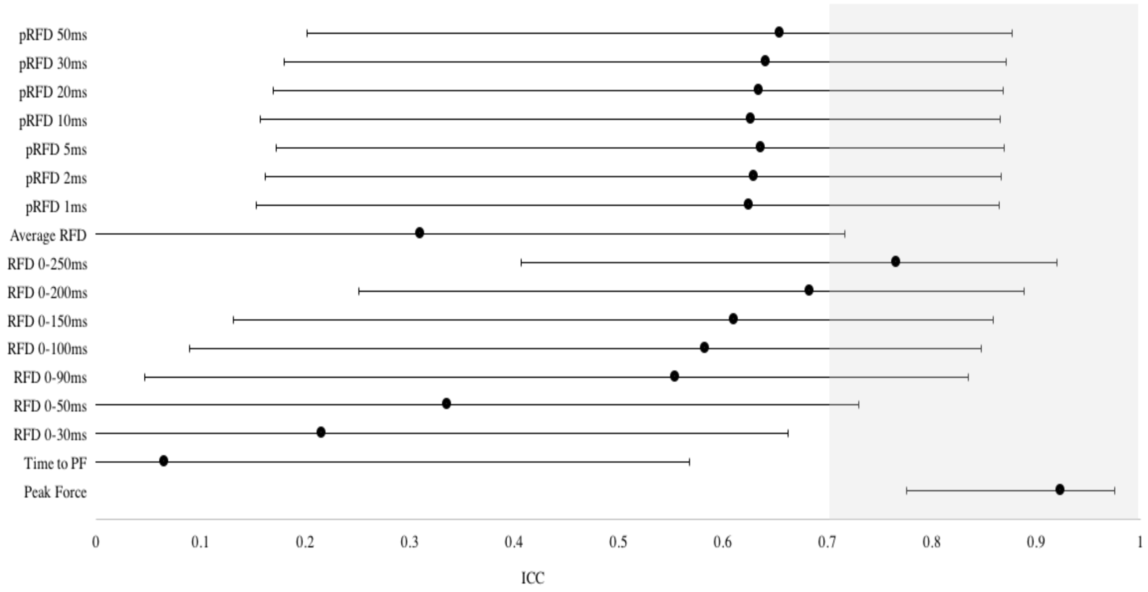

Figure 6. Intraclass coefficient and 90% CI for the isometric peak force test at 125°

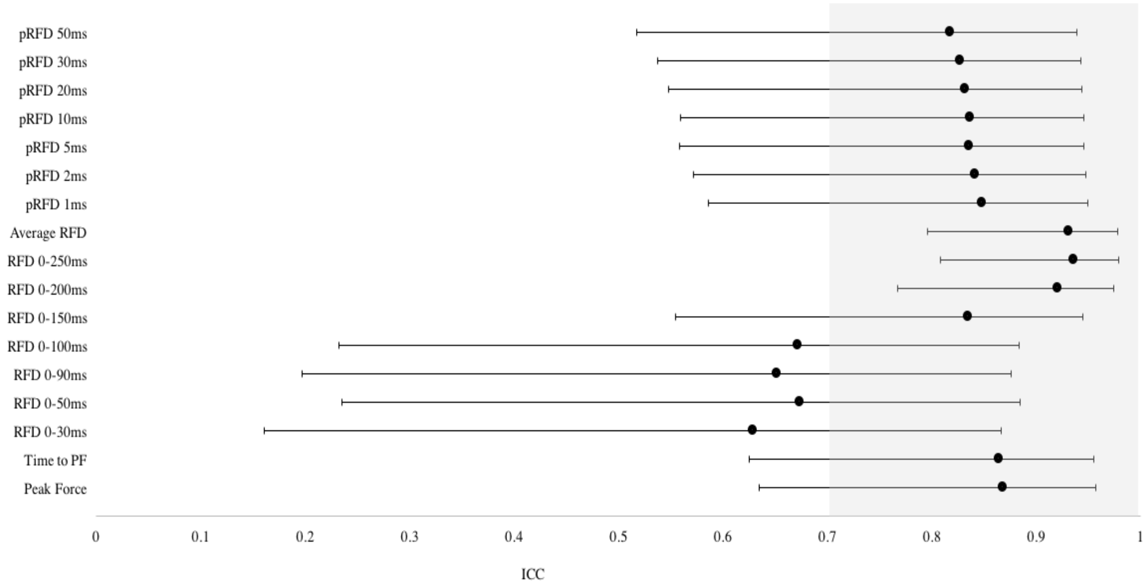

Figure 7. Intraclass coefficient and 90% CI for the isometric explosive force test at 100°

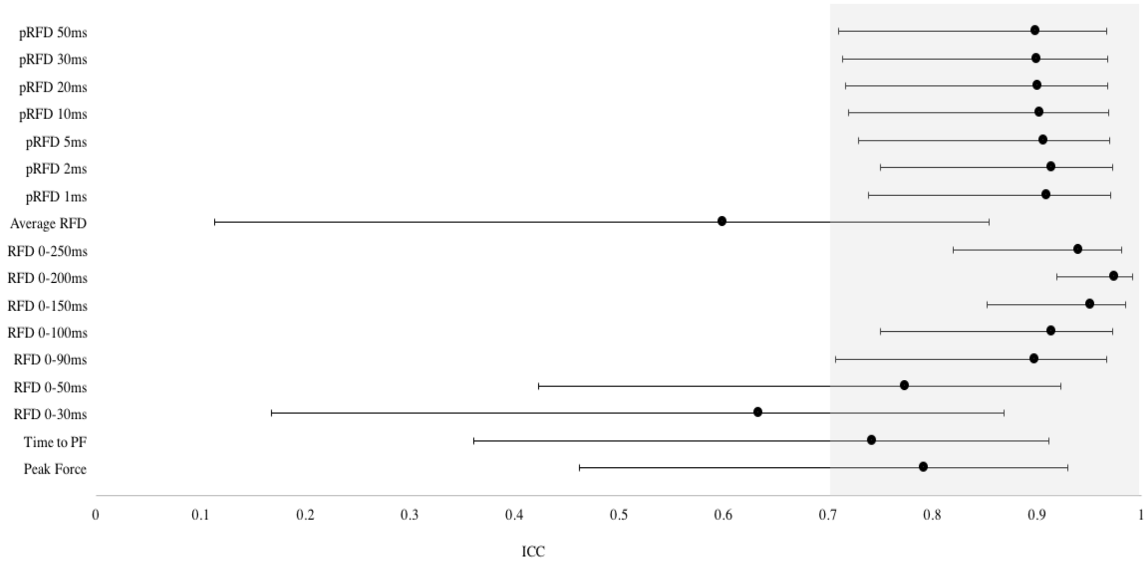

Figure 8. Intraclass coefficient and 90% CI for the isometric explosive force test at 125°