Manuscript Title: Measuring what matters in isometric multi-joint rate of force development

Authors: David Drake[1, 2*], Rodney A. Kennedy[1] and Eric S. Wallace[1]

Department/Institution: [1] School of Sport, Ulster University; [2] Ulster Rugby, Irish Rugby Football Union.

Corresponding Author Details[*]: School of Sport, Ulster University, Jordanstown, Shore Road, Newtownabbey, Co. Antrim, BT37 0QB, N. Ireland.

Email: daviddrake87@gmail.com

Phone: +44 [illegible]

Twitter: @d_drakey

ORCID: orcid.org/0000-0003-0440-7097

Postal address (all authors): As per corresponding author.

Dr Rodney Kennedy: *email* r.kennedy@ulster.ac.uk; *phone* +44 28 90366242

Prof Eric Wallace: *email* es.wallace@ulster.ac.uk; *phone* +44 28 90366535

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Abstract

This study aimed to evaluate responsiveness (ability to detect change) of isometric force-time measures to neuromuscular fatigue in resistance-trained participants using two differing protocols that modified both the instructions provided to participants and the duration of the test. Both protocols were completed at two knee joint angles in the isometric squat test. Ten participants volunteered to take part in this study (age: 27.0±4.5 years, strength training experience: 7.7 ± 2.6 years. Isometric peak force (ISqT^{peak}) and isometric explosive force (ISqT^{exp}) test protocols were assessed at two joint angles (knee angle 100° and 125°) pre-high intensity strength training, immediately post strength training, 24 hours post, 48 hours post and analysed for peak and RFD performance. Participants completed eight sets of three repetitions of the back-squat exercise as the high intensity strength training. Results showed the highest standardised response means (SRM) detected was peak force using the ISqT^{peak} 100, SRM -1.97 compared to an SRM of -1.31 for RFD 200 ms in the ISqT^{exp} 125. Peak force was the most responsive variable using the ISqT^{peak} protocol, whereas the ISqT^{exp} protocol was most responsive for RFD measures. Therefore, ISqT^{peak} and ISqT^{exp} test protocols should not be used interchangeably to evaluate RFD variables.

Keywords: responsiveness; explosive force; maximal strength; neuromuscular performance

Introduction

Resistance training is the primary method of eliciting both neural and structural changes in neuromuscular performance (Aagaard, 2003), and has been subject to multiple reviews of the associated adaptation to stimuli and program variables (Davies, Kuang, Orr, Halaki, & Hackett, 2017; Ratamess et al., 2009; Rhea, Alvar, Burkett, & Ball, 2003; Schoenfeld, Grgic, Ogborn, & Krieger, 2017; Schoenfeld, Ogborn, & Krieger, 2016a, 2016b; Suchomel, Nimphius, Bellon, & Stone, 2018). Perhaps the most functionally relevant adaptation elicited from resistance training is improved rate of force development (RFD) (Aagaard, 2003). RFD is typically a measure determined through isometric testing reflecting the physical quality of rapid force production, often referred to as explosive strength (Andersen, Andersen, Zebis, & Aagaard, 2010; Folland, Buckthorpe, & Hannah, 2014). Enhancements in explosive strength are preferential for sports performance (Andersen et al., 2010) and may increase the ability to make rapid postural corrections which could reduce the potential for injuries or falls in elderly persons (Folland et al., 2014). In a sports context such as sprinting, a key determinant of sprinting fast is the ability to apply greater forces relative to body mass into the ground in short ground contact times (Clark & Weyand, 2014; Moir, Brimmer, Snyder, Connaboy, & Lamont, 2018). As such explosive strength is an important neuromuscular capability that influences the performance of time limited motor tasks in sport and daily living (Kennedy & Drake, 2018a; Rodríguez-Rosell, Pareja-Blanco, Aagaard, & González-Badillo, 2018). Neuromuscular assessment should therefore reflect the demands of sport and daily living, through the assessment of neuromuscular status under time limited constraints.

Isometric multi-joint tests are used to monitor adaptation of strength qualities (Brady, Harrison, Flanagan, Haff, & Comyns, 2017; Haff, Ruben, Lider, Twine, & Cormie, 2015; Rodríguez-Rosell et al., 2018). The analysis of the force-time trace enables the calculation of multiple measures of interest, which includes RFD, peak force and the ability to examine RFD in sport specific time ranges (Andersen et al., 2010; Folland et al., 2014). Whilst these measures have been subject to reliability investigations, little is known as to which variables are practically useful in detecting changes resulting from training adaptations or fatigue. For neuromuscular measures to be adopted into practice, further research is required to determine the responsiveness of force-time measures. Knowledge of responsive measures enables monitoring of neuromuscular adaptation from which coaches can appropriately modify interventions (McLean, Coutts, Kelly, McGuigan, & Cormack, 2010). Studies adopting this approach are limited (Crowcroft, McCleave, Slattery, & Coutts, 2017; Kennedy & Drake, 2018b; Roe et al., 2016), with no studies using isometric-multi joint strength tests to assess explosive strength. Hornsby et al. (2017) has shown evidence for greater signal from RFD measures compared to peak force measures, describing the observation as RFD having greater sensitivity. However, with absence of the 'noise' within this study the statistical determination of responsiveness is not possible.

Responsiveness (also termed sensitivity to change) is the ability of a measure to detect change over time (Norman, Wyrwich, & Patrick, 2007). Despite being identified as a critical component of validity (Impellizzeri & Marcora, 2009; Norman et al., 2007; Robertson, Kremer, Aisbett, Tran, & Cerin, 2017), responsiveness of performance tests are scarcely evaluated within sports science (Fanchini et al., 2015). A predominant focus has been on reliability of measures, which provides evidence for the 'noise' of a measure in a population but not the ability of a measure to detect change. That said, a measure with a large typical error 'noise' that responds to training with a large magnitude (signal) can be more responsive and useful than a measure with a low typical error but responds to training with a low magnitude (Buchheit, 2014). As such decision making on the efficacy of performance measures should be evaluated in terms of responsiveness and not based on reliability measures in isolation (Fanchini et al., 2014; Impellizzeri & Marcora, 2009). This concept has not been investigated using isometric multi-joint tests. A common view is that RFD measures are less reliable than peak force (Maffiuletti et al., 2016). Leading to certain neuromuscular measures disregarded in practice based on arbitrary reliability thresholds. An example of this is stated within Bazyler, Sato, Wassinger, Lamont, and Stone (2014) "RFD at 50 and 90 milliseconds with 120° were excluded because of low test-retest reliability (ICC < 0.7)" (Bazyler et al., 2014). Therefore, the assessment of responsiveness in isometric multi-joint tests including comparisons of how differing testing protocols affect responsiveness would offer greater evidence for this critical component of test validity.

Whilst the premise of the signal to noise ratio is intuitive, the statistical procedures underpinning responsiveness has been widely discussed. A family of analytical methods to assess responsiveness exist (Husted, Cook, Farewell, & Gladman, 2000). However with no gold standard method to determine responsiveness (Stratford & Riddle, 2005) and a growing range of potential approaches, selecting the appropriate responsiveness statistic can be confusing for researchers and practitioners (Norman et al., 2007; Stratford & Riddle, 2005). The choice of the appropriate responsiveness statistic should be guided by the characteristics of the sample, the type of design and the homogeneity of the change expected (García de Yébenes Prous, Salvanés, & Ortells, 2008; Stratford & Riddle, 2005). The determination of responsiveness provides a ratio of "signal" (the observed change) to "noise" (a measure of variance due to error and biological variation) (Beaton, Hogg-Johnson, & Bombardier, 1997; Impellizzeri & Marcora, 2009; Norman et al., 2007), from which practical decisions can be made when selecting measures. In the same manner as reliability should be interpreted, responsiveness in a measure of a test or variable applied in a given context and population

(Norman et al., 2007). As suggested by Impellizzeri and Marcora (2009), more rigorous methods in the validation of physiological and performance testing may serve to improve both the quality of sport science research and professional practice. In the contest of RFD measures, enhanced methodological approaches may result in better understanding of the neuromuscular response to exercise.

Given high intensity resistance training is a routine training modality in elite sport, surprisingly little is known about the neuromuscular response resulting from one maximal strength session. Brandon, Howatson, Strachan, and Hunter (2015) detailed the acute neuromuscular response following the back-squat exercise performed with three different loads in an elite group of athletes. Increased understanding of the neuromuscular response to maximum strength training is needed to ensure optimal adaptation, particularly in resistance trained populations (Howatson, Brandon, & Hunter, 2015). Additionally, high intensity resistance training over longer training blocks with inadequate recovery periods may result in sub-optimal neuromuscular status or overtraining (Raeder et al., 2016). As such there is a need for surrogate markers of neuromuscular status that are practical to implement without disturbing the training process (Raeder et al., 2016). Moreover, Andersen et al. (2010) recommends that further studies examining the effects of different types of resistance training on RFD measures may improve the design of optimal training programs.

Whilst previous studies assessing isometric multi joint RFD and peak force have used one test protocol to assess both rate and peak force capacity (Brady et al., 2017; Haff et al., 2015). Recent work has demonstrated advantages to assessing peak force and RFD using differing protocols (Drake, Kennedy, & Wallace, 2019). These protocols allow for further exploration of optimal methods to ascertain practically useful force-time measurements. The aim of this study was to evaluate the responsiveness of force-time measures to neuromuscular fatigue in resistance-trained participants using two instructive protocols and two angles in the isometric squat test. Secondly this study aimed to assess the neuromuscular response to a high intensity strength training intervention over a forty-eight hour time course.

Methods

Participants

Eight male and two female participants volunteered to take part in this study (age: 27.0±4.5 years, height: 1.79 ± 7.6 m, mass: 81.6 ± 12.9 kg, strength training experience: 7.7 ± 2.6 years, relative strength in isometric squat 100°: 2.38 ± 0.36 N/kg). Ethical approval was granted by the University institutional review board (Ulster University) prior to the study commencing. Participants provided written informed consent prior to the study.

Experimental design

Participants completed three familiarisation sessions prior to undertaking the study (Drake, Kennedy, & Wallace, 2018). Familiarisation involved three repetitions following two different instructions which were replicated at the two testing angles. On three consecutive days at the same time of day (Teo, McGuigan, & Newton, 2011), participants attended our laboratory to complete the resistance training and neuromuscular testing protocol. Neuromuscular testing was completed on day one followed by the training intervention (detailed below). After the training intervention, participants completed the neuromuscular testing five minutes post the training. Twenty-four and forty-eight hours post training intervention participants returned to the lab to assess the neuromuscular recovery. Participants confirmed their maintenance of normal physical activity level and nutritional intake across all days of study participation.

Participants did not undertake any additional training and were not taking any ergogenic supplement throughout involvement in this study.

Training protocol and monitoring

In accordance evidence and recommendations by Ratamess et al. (2009), we used a high intensity resistance (three repetitions per set), multi-joint exercise (back squat) intervention to maximize the overall strength stimulus. The back-squat exercise is commonly used in resistance exercise to enhance strength capacity (Brandon et al., 2015; Rahmani, Viale, Dalleau, & Lacour, 2001; Thomas et al., 2018). The use of this exercise allowed for standarisation of variables such as range of movement, repetition velocity, and relative intensity. With respect to volume of sets we opted for eight sets based on the work of (Rhea et al., 2003), who demonstrate this to be the optimal volume per muscle group to elicit strength adaptation. This high volume of sets within one training session has been used to evaluate neuromuscular fatigue in resistance trained participants (Brandon et al., 2015; McCaulley et al., 2009; Storey, Wong, Smith, & Marshall, 2012; Thomas et al., 2018). A standardised rest period of four minutes between each set to reduce potential for between set performance decrements (Ratamess et al., 2009), and to maximize the load lifted. Participants were individually supervised by an experienced strength and conditioning coach to monitor the training session. Participants performed the back-squat exercise to a knee angle of 90°, measured using a handheld goniometer (66fit Ltd, Lincolnshire, UK). An adjustable metal box was used to provide a consistency of vertical displacement of each repetition. Every repetition was monitored for range of motion and velocity using a linear position transducer (GymAware, Kinetic Performance Technologies, Canberra, Australia) and subsequently analyzed using custom software (GymAware Version 3.13, Kinetic Performance Technologies). Concentric velocity of each repetition was used to inform loading adjustments for participants based on the critical velocity to successfully complete a maximal squat trial (Loturco et al., 2016). To ensure the resistance training session was performed to high intensity, participants rated their perceived exertion post each set using the CR-10 RPE scale (Day, McGuigan, Brice, & Foster, 2004; Raeder et al., 2016). This scale is accompanied by the descriptive ratings of 0 representing no effort and 10 representing maximal effort.

Neuromuscular assessment

Participants completed a standardized warm up comprising repetitions of the isometric squat at self-estimated 75% and 90% of maximal effort prior to beginning testing at the 100° angle. Participants completed maximal isometric squat tests following two differing instructive protocols which are known to affect the measurement outcome (Drake et al., 2019). The isometric squat peak force test ($ISqT^{peak}$) for a three second duration and the isometric squat explosive force test ($ISqT^{exp}$) for a one second duration. Both instructive protocols were performed at two testing angles (external knee flexion angle 100° and 125°). The order of isometric testing was both the $ISqT^{peak}$ and $ISqT^{exp}$ test at the 100° angle, which was then repeated at the 125° angle.

Testing was performed on a custom isometric rack (Samson Equipment Inc, NM, USA) integrated with 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). Force plates were zeroed whilst participants remained static on the plates with hands on hips, therefore zero force reflects the participants' bodyweight. Participants testing positions were standardised prior to each trial, and confirmed using goniometry (66fit Ltd Lincolnshire, UK) by measuring the knee and hip joint angle (100° corresponded to a hip angle of 149 ± 3.56°; 125° corresponded to a hip angle of 160 ± 2.12°). Participants' received visual biofeedback of real-time force trace using a mounted screen placed directly in front of the isometric rack enabling participants to observe a steady baseline period of force for one second prior to contraction onset. Sampled force signals for each trial was then visually inspected by the lead investigator and were manually discarded when a countermovement was visibly detected on the force-time trace during the pre-contraction period. Trials were discarded and repeated if the participant deemed that the trial was not representative of their true maximal effort.

Isometric peak force test

The isometric peak force test completed with the goal to produce the highest force possible. Participants were instructed to hold a minimal and steady baseline force for one second prior to maximal contraction and then to "push against the bar as hard and as fast as possible" for three seconds, which is the typical duration and instruction used in isometric multi-joint tests with this goal (Drake, Kennedy, & Wallace, 2017). Two trials were completed with two minutes' rest provided between trials.

Isometric explosive force test

The isometric explosive force test was used with the primary goal to produce the highest force as fast as possible. Participants were instructed to hold a minimal and steady baseline force for one second prior to maximal contraction and then 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.

Isometric force trace analysis

Sampled vertical force signal was subsequently smoothed using a 12ms moving half-width in a custom excel spreadsheet (Drake et al., 2019). An extensive menu of force-time variables was calculated for responsiveness analysis. Variables were chosen based on those presented commonly within published literature (Brady et al., 2017; Dos'Santos, Thomas, Jones, McMahon, & Comfort, 2017; Drake et al., 2019; Haff et al., 2015). The variables assessed were: peak force, time to peak force, rate of force development at time points 0–50, 0–100, 0–150, 0–200, 0–250 ms and average. Peak instantaneous RFD (pRFD) was assessed in 5, 10, 20 and 50 millisecond sampling windows. The starting point of each trial was defined as the last instantaneous point along the rate of force-time trace were the value was zero using a post-trial backwards search of the force signal (Drake et al., 2019). The best trials were identified based on the RFD 200ms variable, then the two best trials for each test were average for further analysis.

Assessment of muscle soreness

Participants provided a subjective rating of their muscle soreness on a visual analogue scale (VAS) prior to commencing any activity of each day. The VAS was a 100mm line with endpoints labeled by "no pain" (left) and "unbearable pain" (right). Participants marked a vertical line at a point reflecting their pain at the time of measurement, which was subsequently measured in mm from the left side of the scale to the participants marking (Raeder et al., 2016; Thomas et al., 2018).

Statistical analysis

Prior to analysis data was visually inspected for normality with a Shapiro-Wilks test implemented to check the normality of the data distribution. Levene's test was used for the assessment of the homogeneity of variance. These tests were performed using IBM SPSS

Statistics 22 software (SPSS Inc., Chicago, IL, USA). The responsiveness of measures to the training intervention was assessed at twenty-four hours post intervention using the standardized response mean (SRM), McCaulley et al. (2009) has shown the greatest neuromuscular disturbance occurs at 24hours post resistance exercise. The SRM is a ratio of the observed change (signal) and the standard deviation of the change scores (noise), previously referred to as the signal:noise ratio. Values of 0.20, 0.50, 0.80 or greater define the magnitude of responsiveness to represent small, moderate and large effects respectively (Husted et al., 2000), with 90% confidence intervals calculated around the SRM based on the observed changes being normally distributed (Beaton et al., 1997). Practical inferences about the magnitude of change in force time variables across time points were made using the procedures detailed by Hopkins, Marshall, Batterham, and Hanin (2009). This analysis used a threshold of 0.2 x between participant SD as the smallest practical effect, based on Cohen's d effect sizes (ES) values (trivial, <0.2; small, 0.2-0.6, moderate; 0.6-1.2, large, 1.2-2.0; and very large, ≥2.0. The likelihood that the standardized change across time points was positive, trivial or negative was calculated with the accuracy of these effects described in probabilistic terms using the following scale: <0.5%, most unlikely; 0.5–5%, very unlikely; 5–25%, unlikely; 25–75%, possibly; 75–95%, likely; 95–99.5%, very likely; >99.5%, most likely. Where the 90% CI of the ES crossed both ± 0.2 the effects were reported as unclear (Hopkins et al., 2009). The reliability of the force time measures used within the present study have been previously investigated using the above methods within our laboratory and are detailed in Drake et al. (2019).

Results

Strength training intervention

Post session RPE was 7.7 ± 0.30, the minimum concentric velocity across each set was 0.32 ± 0.05 $m \cdot s^{-1}$, and the total load lifted across the training session was 27, 774 ± 5751 kg. The estimated time under tension per squat repetition was four seconds, resulting in a session load of approximately 96 seconds of time under tension.

Assessment of muscle soreness

Muscle soreness VAS prior to the training intervention was 5.60 ± 3.81mm, with increases in soreness reported at 24 (VAS = 32.60 ± 8.56mm) and 48 hours (VAS = 26.60 ± 6.99mm) post training. The magnitude of the increase in soreness at 24 hours was almost certainly very large (ES = 8.56, CI = 6.76 to 10.37, $p < 0.000$) and at 48 hours was almost certainly very large (ES = 6.99, CI = 5.47 to 8.51, $p < 0.000$). A likely large decrease in soreness was observed from 24 to 48-hour time points (ES = -1.58, CI = -3.15 to 0.00, $p = 0.100$).

Assessment of responsiveness

Unclear and possible moderate SRM effects were found for $ISqT^{peak}$ 100 in force time measures at set time points and peak RFD respectively. Likely moderate SRM effects were found for $ISqT^{peak}$ 125 in force time measures at set time points and peak RFD. Very likely large effects were found for the RFD 250 ms variable in the $ISqT^{peak}$ 125. Unclear SRM effects were found for RFD ≤100 ms, with very likely large SRM effects found for RFD ≥ 200 ms in the $ISqT^{exp}$ 100. Likely moderate SRM effects were found for all peak RFD variables in the $ISqT^{exp}$ 100. Very likely or almost certainly large effects were found for force time measures at set time points and peak RFD in the $ISqT^{exp}$. Very likely or almost certainly large effects were found for peak force in all isometric tests. Magnitude of SRM effects for testing angle and test type and their associated 90% CI are presented in table 1.

Acute neuromuscular response

Peak force SRM affects

Immediately post intervention there was almost certain large decrease in the $ISqT^{peak}$ 100 and $ISqT^{peak}$ 125 (p = 0.002 and 0.003 respectively), very likely large decrease in the $ISqT^{exp}$ 100 and likely small decrease in the $ISqT^{exp}$ 125 (p = 0.030 and 0.155 respectively). Twenty-four hours post intervention almost certain large decreases in the $ISqT^{peak}$ 100 and $ISqT^{peak}$ 125 (p = 0.000 and 0.004 respectively) and very likely large decreases in the $ISqT^{exp}$ 100 and $ISqT^{exp}$ 125 (p = 0.029 and 0.025 respectively). Forty-eight hours post intervention affects were very likely large decrease in the $ISqT^{peak}$ 100 (p = 0.012), likely moderate decrease $ISqT^{peak}$ 125 (p = 0.058), likely moderate decrease $ISqT^{exp}$ 100 (p = 0.108), very likely large decrease $ISqT^{exp}$ 125 (p = 0.009). Magnitude of effects for the time course recovery of the peak force variable presented in table 2.

RFD 200ms SRM affects

Immediately post intervention there was unclear affects in the $ISqT^{peak}$ 100 (p = 0.759), likely moderate decrease in the $ISqT^{peak}$ 125 (p = 0.039), likely moderate decrease in the $ISqT^{exp}$ 100 (p = 0.071) and likely small decrease in the $ISqT^{exp}$ 125 (p = 0.161). Twenty-four hours post intervention there was unclear affects in the $ISqT^{peak}$ 100 (p = 0.434), likely moderate decrease in the $ISqT^{peak}$ 125 (p = 0.046), very likely large decrease in the $ISqT^{exp}$ 100 (p = 0.029) and almost certain large decrease in the $ISqT^{exp}$ 125 (p = 0.005). Forty-eight hours post intervention there was unclear affects in the $ISqT^{peak}$ 100 (p = 0.402), likely small decrease in the $ISqT^{peak}$ 125 (p = 0.182), likely moderate decrease in the $ISqT^{exp}$ 100 (p = 0.038) and almost certain large decrease in the $ISqT^{exp}$ 125 (p = 0.002). Magnitude of effects for the time course recovery of the RFD 0-200ms variable presented in table 3.

Discussion

Ensuring the validity of RFD measures to evaluate the neuromuscular response to resistance exercise is of critical importance to be adopted in practice. Whilst our previous work has explored the reliability of measures in both isometric peak and explosive test protocols at two knee angles (Drake et al., 2019), the selection of appropriate measures should not only be based reliability statistics. Measured variables should be selected from the force-time trace that demonstrate responsiveness to an intervention, thus avoiding unsubstantiated measures that do not advance research and practice (Kennedy & Drake, 2018b). This study provides clear evidence that RFD variables within set time bands from contraction onset increase responsiveness as duration from contraction onset increases. This trend occurs for across test protocols and test angles (see table 1). Contrary to recommendations from our previous work states RFD measures <150 ms are not reliable (Drake et al., 2019), however these measures may offer insight into the neuromuscular adaptation to an intervention. Therefore, the measures responsiveness should direct its use in the training – monitoring cycle. If the researcher or practitioner is interested in early RFD the $ISqT^{exp}$ 125 protocol should be utilised (see SRM table) given its greater degree of responsiveness compared to the peak force protocol or indeed the 100° testing angle.

The SRM of peak RFD variables we observed very likely large effects in the $ISqT^{exp}$ 125 protocol with possible moderate effects in the $ISqT^{peak}$ 100 protocol. This measure may have a degree of efficacy but due to the increased ‘noise’ resultant from inconsistency in the point on the force-time trace being assessed (Maffiuletti et al., 2016) and the SRM magnitude is not improved by increased time epochs, peak RFD does not offer any additional benefit in practice to detect change when compared to RFD measures at set time points. RFD at 250 ms in $ISqT^{exp}$ 125 protocol offers the most responsive RFD measure to the acute strength intervention and should be preferentially selected to assess adaptation from strength training

Arguments that RFD is more responsive to strength training volume than peak force (Hornsby et al., 2017) is not directly supported within our findings. The greatest NM disturbance within our study was peak force using the $ISqT^{peak}$ 100, SRM -1.97 compared to an SRM of -1.31 for RFD 200 ms in the $ISqT^{exp}$ 125 (Table 1). Despite the argument that RFD in more responsive to strength training volume (Hornsby et al., 2017), their effect size data shows the greatest neuromuscular disturbance is the peak force variable in male participants whereby the change in signal is twice the magnitude of RFD (seen at time-points 2 to 3 and 3 to 4 and 4 to 5). Work by Crameri et al. (2007) also reports greater responsiveness of RFD compared to Peak force (MVC) following a high volume of slow and fast isokinetic leg extensions. However, this comparison is based on % change and does not account for the variability of the within group changes. To allow between study comparisons, we subsequently calculated standardized mean differences (Cohen's d) using reported group mean and SD data for two studies (Crameri et al., 2007; Molina & Denadai, 2012). Effect size data from (Crameri et al., 2007) revealed peak force had the greatest neuromuscular disturbance at twenty-four hours post (ES = 2.5) compared to RFD 50 ms (ES = 1.65), RFD 100 ms (ES = 1.79). Similarly, effects from Molina and Denadai (2012) showed peak torque force had the greatest neuromuscular disturbance at twenty-four hours post 10x10 eccentric knee extensor contractions (ES = 0.71) compared to peak RFD (ES = 0.55). Our study demonstrates peak force is comparably responsive as RFD measures, however this is dependent on the test protocol and testing angle used. RFD measures using the $ISqT^{peak}$ protocol are less responsive than peak force in accordance with the literature discussed above. It is important to note that studies discussed above did not assess responsiveness in the same manner undertaken in our present study (SRM).

Despite common use in practice, the neuromuscular time course response to high intensity strength training protocols is limited in strength trained populations (Brandon et al., 2015). Understanding of the neuromuscular time course response enables the appropriate optimal load-adaptation cycle within training programs (Kennedy & Drake, 2018a; Thomas et al., 2018). Howatson et al. (2015) investigated 4 x 5 back squat and split squats at a high relative intensity, resulting in a significant neuromuscular disturbance in peak force twenty-four hours post intervention (ES = 0.23, $p < 0.05$). Kennedy and Drake (2018a) previously found isometric peak force assessed in an isometric squat test at 90° knee angle had recovered within forty-eight hours following high intensity strength intervention (ES = 0.0, p = > 0.05) following a significant disturbance immediately post (ES = 0.6, p = < 0.001). In congruence with our present study, Thomas et al. (2018) demonstrates that significant neuromuscular disturbance remains forty-eight hours post 10x5 back squats in trained participants (ES = 0.64, $p < 0.05$), this study used isometric knee extensions form 90° knee angle as the neuromuscular test. Results from our present study show almost certain moderate (ES = -0.71, $p = 0.000$) and very likely small decreases (ES = -0.5, $p = 0.004$) in peak force in the $ISqT^{peak}$ 100 and $ISqT^{peak}$ 125 tests respectively at twenty-four hours. Meanwhile at forty-eight hours post strength intervention likely small (ES = -0.42, $p = 0.012$) and likely small decreases (ES = -0.39, $p = 0.058$) in peak force in the $ISqT^{peak}$ 100 and $ISqT^{peak}$ 125 tests were observed. Putting our findings in context with existing evidence from high intensity strength training interventions in strength trained participants, a period of twenty-four hours recovery results is the time point where the greatest neuromuscular disturbance in observed peak force capacity. With a likelihood that capacity to produce peak force will still be affected up to forty-eight hours even in experienced strength trained participants, a minimum recovery period of forty-eight hours should be planned between high intensity strength training. This finding is further supported by the very large increase in muscle soreness at the forty-eight hour time point.

Our study demonstrates a novel approach to assess the RFD capacity across the recovery-time course following a maximal strength intervention by incorporating two instructive protocol and two testing angles. McCaulley et al. (2009) evaluates 11 sets of 3 repetitions at 90%1RM using an isometric peak force test at 100° knee angle. Finding significantly decreased RFD post high intensity strength intervention at twenty-four hours post, however no significant decrease was present at forty-eight hours. This in in agreement with our study at the comparable angle ($ISqT^{peak}$ 100) whereby we found a possible trivial decrease in RFD 200 (ES = -0.15, p = 0.402). In contrast, we found the $ISqT^{exp}$ 100 and 125 test protocols to reveal likely small (ES = -0.49, p = 0.038) and almost certainly moderate (ES = -0.68, p = 0.002) decreases in RFD respectively at forty-eight hours. Whilst between the twenty-four to forty-eight hour measurements a trend for improved RFD capacity is evident in our results, we observe that forty-eight hours recovery post high intensity strength training may not be sufficient for full recovery of RFD capacity. This finding transpires through the results of the $ISqT^{exp}$ test protocol (Figure 1). As such we recommend that $ISqT^{peak}$ and $ISqT^{exp}$ test protocols should not be used interchangeably to evaluate RFD variables. Use of the $ISqT^{exp}$ test may offer important implications for subsequent exercise prescription post high intensity strength training with respect to the of the day to day plan for athletes.

Conclusion

Measuring variables that demonstrate responsiveness is a critical component of validity surrounding neuromuscular assessments. This clinimetric property moves beyond the inclusion of variables based solely on reliability thresholds by presenting isometric force time measures evidenced for responsiveness to a strength intervention. Our study finds peak force variable is most responsive using the $ISqT^{peak}$ protocol, whereas the $ISqT^{exp}$ protocol is best for assessing

RFD measures. The 125° testing angle is the optimal angle for evaluating RFD measures. The neuromuscular disturbance caused by a high intensity strength intervention may not be fully recovered following 48 hours, therefore careful monitoring of force time variables may support practitioners in the optimal loading of the neuromuscular system of athletes.

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Figure

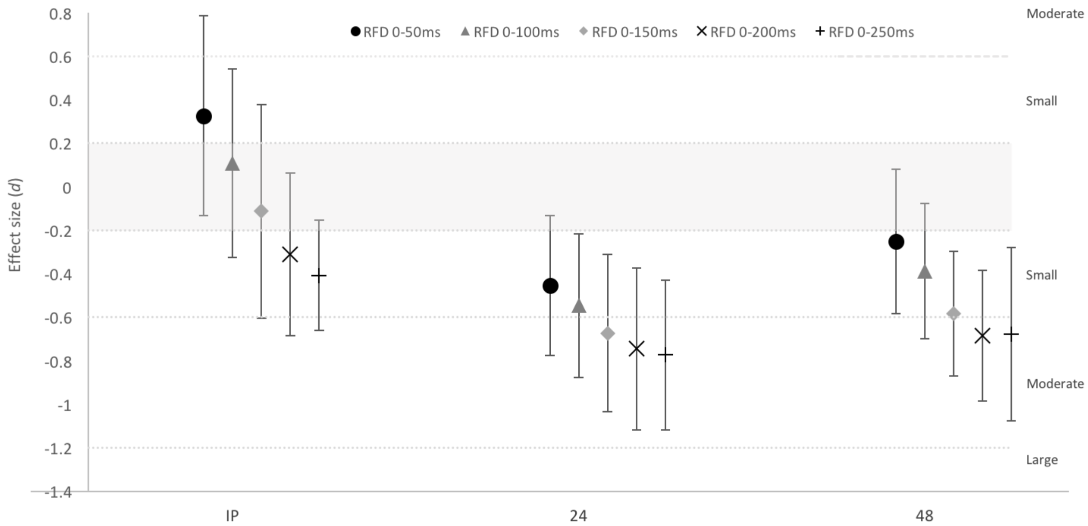

Figure 1. Change in neuromuscular performance (Effect size) from high intensity strength training at time periods; immediately post (IP), 24-hours post (24), and 48-hours post (48), evaluated in the IsqT^{exp} 125. Grey shaded area corresponds to unclear effects.

Table 1

Table 1. SRM effects at twenty-four hours post intervention compared between testing protocol and testing angle. Magnitude of the SRM inference represented by no shading if unclear, lightest grey ≥ 0.20, middle grey tone ≥ 0.50, and dark grey tone ≥ 0.80.

		$ISqT^{peak}$ 100	**$ISqT^{peak}$ 125**	**$ISqT^{exp}$ 100**	**$ISqT^{exp}$ 125**
Peak force	SRM	-1.97	-1.21	-0.82	-0.85
	90% CI	(-2.55 to -1.39)	(-1.79 to -0.63)	(-1.40 to -0.24)	(-1.43 to -0.27)
	Probabilistic inference	Almost certainly large	Almost certainly large	Very likely large	Very likely large
Time to peak force	SRM	0.55	0.5	-0.04	0.88
	90% CI	(-0.03 to 1.13)	(-0.08 to 1.08)	(-0.62 to 0.54)	(0.30 to 1.46)
	Probabilistic inference	Possible moderate	Possible moderate	Unclear	Very likely large
RFD 0-50ms	SRM	-0.35	-0.32	0.18	-0.82
	90% CI	(-0.93 to 0.23)	(-0.90 to 0.26)	(-0.40 to 0.76)	(-1.40 to -0.24)
	Probabilistic inference	Unclear	Unclear	Unclear	Very likely large
RFD 0-100ms	SRM	-0.23	-0.52	-0.13	-0.96
	90% CI	(-0.81 to 0.35)	(-1.10 to 0.06)	(-0.71 to 0.45)	(-1.54 to -0.38)
	Probabilistic inference	Unclear	Possible moderate	Unclear	Very likely large
RFD 0-150ms	SRM	-0.23	-0.69	-0.45	-1.08
	90% CI	(-0.81 to 0.35)	(-1.27 to -0.11)	(-1.03 to 0.13)	(-1.66 to -0.50)
	Probabilistic inference	Unclear	Likely moderate	Possible small	Very likely large
RFD 0-200ms	SRM	-0.26	-0.73	-0.82	-1.16
	90% CI	(-0.84 to 0.32)	(-1.31 to -0.15)	(-1.40 to -0.24)	(-1.74 to -0.58)
	Probabilistic inference	Unclear	Likely moderate	Very likely large	Almost certainly large
RFD 0-250ms	SRM	-0.4	-0.98	-0.9	-1.31

	90% CI	(-0.98 to 0.18)	(-1.56 to -0.40)	(-1.48 to -0.32)	(-1.89 to -0.73)
	Probabilistic inference	Possible small	Very likely large	Very likely large	Almost certainly large
pRFD 5ms	SRM	-0.56	-0.65	-0.66	-1
	90% CI	(-1.14 to 0.02)	(-1.23 to -0.07)	(-1.24 to -0.08)	(-1.58 to -0.42)
	Probabilistic inference	Possible moderate	Likely moderate	Likely moderate	Very likely large
pRFD 10ms	SRM	-0.54	-0.65	-0.63	-1
	90% CI	(-1.12 to 0.04)	(-1.23 to -0.07)	(-1.21 to -0.05)	(-1.58 to -0.42)
	Probabilistic inference	Possible moderate	Likely moderate	Likely moderate	Very likely large
pRFD 20ms	SRM	-0.53	-0.65	-0.64	-1.01
	90% CI	(-1.11 to 0.05)	(-1.23 to -0.07)	(-1.22 to -0.06)	(-1.59 to -0.43)
	Probabilistic inference	Possible moderate	Likely moderate	Likely moderate	Very likely large
pRFD 50ms	SRM	-0.52	-0.67	-0.69	-1.09
	90% CI	(-1.10 to 0.06)	(-1.25 to -0.09)	(-1.27 to -0.11)	(-1.67 to -0.51)
	Probabilistic inference	Possible moderate	Likely moderate	Likely moderate	Very likely large

Abbreviations: SRM = standardized response mean; 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. Neuromuscular time course response for the peak force variable compared between testing protocol and testing angle.

		$ISqT^{peak}$ 100	**$ISqT^{peak}$ 125**	**$ISqT^{exp}$ 100**	**$ISqT^{exp}$ 125**
IP	ES	-0.84	-0.55	-0.46	-0.34
	90% CI	(-1.19 to -0.48)	(-0.80 to -0.31)	(-0.79 to -0.13)	(-0.74 to 0.06)
	Probabilistic inference	Almost certainly moderate	Very likely small	Likely small	Possible small
	p value	0.0019	0.003	0.030	0.155
24	ES	-0.71	-0.5	-0.37	-0.39
	90% CI	(-0.92 to -0.50)	(-0.73 to -0.26)	(-0.64 to -0.11)	(-0.65 to -0.12)
	Probabilistic inference	Almost certainly moderate	Very likely small	Likely small	Likely small
	p value	0.000	0.004	0.029	0.025
48	ES	-0.42	-0.39	-0.25	-0.78
	90% CI	(-0.67 to -0.17)	(-0.72 to -0.06)	(-0.51 to 0.01)	(-1.20 to -0.35)
	Probabilistic inference	Likely small	Likely small	Possible small	Very likely moderate
	p value	0.012	0.058	0.108	0.009

Abbreviations: IP = immediately post, 24 = twenty-four hours post, 48 = forty-eight hours post.

Table 3

Table 3. Neuromuscular time course response for the RFD 0-200ms variable compared between testing protocol and testing angle.

		$ISqT^{peak}$ 100	**$ISqT^{peak}$ 125**	**$ISqT^{exp}$ 100**	**$ISqT^{exp}$ 125**
IP	ES	-0.07	-0.43	-0.51	-0.31
	90% CI	(-0.49 to 0.34)	(-0.76 to -0.11)	(-0.96 to -0.05)	(-0.69 to 0.06)
	Probabilistic inference	Unclear	Likely small	Likely small	Possible small
	p value	0.759	0.039	0.071	0.161
24	ES	-0.24	-0.57	-0.58	-0.75
	90% CI	(-0.78 to 0.30)	(-1.03 to -0.12)	(-0.98 to -0.17)	(-1.12 to -0.37)
	Probabilistic inference	Unclear	Likely small	Likely small	Very likely moderate
	p value	0.434	0.046	0.029	0.005
48	ES	-0.15	-0.36	-0.49	-0.68
	90% CI	(-0.47 to 0.17)	(-0.82 to 0.10)	(-0.86 to -0.12)	(-0.99 to -0.38)
	Probabilistic inference	Possible trivial	Possible small	Likely small	Almost certainly moderate
	p value	0.402	0.182	0.038	0.002

Abbreviations: IP = immediately post, 24 = twenty-four hours post, 48 = forty-eight hours post.