The Inter-Session Reliability of Isometric Force-Time Variables and the Effects of Filtering and Starting Force

by

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The purposes of the present study were to assess the inter-session reliability of force-time variables recorded during isometric back squats and also to assess the effects of applying a filter to the data prior to analysis and assess the effects of different starting force thresholds on the force-time variables. Eleven resistance trained men (age: 22.5 ± 1.9 years; body mass: 90.3 ± 13.5 kg) attended two sessions where they performed isometric squats on force plates allowing the determination of force-time variables of maximal isometric force (Fmax) and different measures of the rate of force development (RFD). The force-time variables were calculated from both raw and filtered force signals. The start of the force application was determined using force thresholds of 1% or 5% of body mass (BM). Inter-session reliability for the force-time measures was assessed by calculating the intraclass correlation coefficient (ICC) and the coefficient of variation (CV) of the measures. The ICC and CV ranged from 0.03 to 0.96 and 4.6 to 168%, respectively. The application of the filter significantly reduced Fmax and peak RFD (p < 0.004) and increased the reliability of the peak RFD. The use of the 5% BM threshold increased the magnitude of many of the RFD measures (p < 0.004) and resulted in slight improvements in the reliability of these measures although the resulting temporal shift in the force-time signal would preclude accurate assessment of the early phase of the RFD (< 100 ms). The use of a 1% BM starting force threshold without a filter is recommended when using the isometric back squat protocol presented here. Furthermore, the RFD calculated within specific time intervals is recommended.

Key words: *isometric back squat, isometric force, rate of force development, reliability.*

Introduction

Explosive strength has been defined as the ability to produce large force or torque values in a limited period of time with high rates of force development (RFD) (Schmidtbleicher, 1992). The requirement of producing force rapidly is important given that many sporting performances are limited by the time available to the athlete to develop force (Dapena and Chung, 1988; Kuitunen et al., 2002; Luhtanen and Komi, 1979; Viitasalo et al., 1981; Maszczyk et al., 2016). Indeed, the RFD has been one of the most important variables in explaining performance during tasks where large acceleration is required (Aagaard et al., 2002; Cronin et al., 2004; González-Badillo et al., 2010). Previous authors have divided the RFD into early

(<100 ms) and late (>200 ms) phases and demonstrated that these phases are related to intrinsic neuromuscular properties and maximal force capabilities, respectively (Andersen and Aagaard, 2006). The early and late phases of the RFD have been shown to respond differently to a period of high-intensity resistance training (Andersen et al., 2010). Additionally, RFD measures have been employed as sensitive markers to muscular fatigue following different exercise regimens (Molina and Denadai, 2012; Thorlund et al., 2008, 2009, 2011). Therefore, accurate measurement of the RFD is important in the assessment of various athletic populations.

The RFD has been measured during many

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different tasks including dynamic movements such as the vertical jump (McLellan et al., 2011; Moir et al., 2009; Golas et al., 2017), mid-thigh clean pulls (Haff et al., 1997; Khamoui et al., 2011), as well as during isometric tasks (Bazyler et al., 2015; Haff et al., 1997, 2015; Marcora and Miller, 2000; Nuzzo et al., 2008). While only small to moderate correlations have been reported between measures of the isometric RFD and performance during dynamic movements such as vertical jumps and squats (Bazyler et al., 2015; Haff et al., 1997; Khamoui et al., 2011; Marcora and Miller, 2000), large correlations have been reported between the RFD measured during isometric and dynamic mid-thigh pulls (Haff et al., 1997). The relationship between isometric and dynamic measures is important because isometric tests have been proposed to require less skill, less time to administer and potentially involve less muscle damage (Moir, 2012). Furthermore, measures of maximal strength (peak force) as well as explosive strength (RFD) can be assessed concurrently during isometric tests of strength.

There are many different methodologies used in the extant literature to measure the isometric RFD. For example, some authors have recorded the peak RFD (Haff et al., 1997, 2015; Marcora and Miller, 2000), while others have measured the RFD during specific time periods from 50 to 250 ms (Andersen et al., 2010; Bazyler et al., 2015; Khamoui et al., 2011). The raw force signal has been passed through a filter or subjected to a smoothing procedure prior to the calculation of the RFD in some protocols (Andersen et al., 2010; Bazyler et al., 2015; Haff et al., 2015), but not in others (Haff et al., 1997; Kawamori et al., 2006; Khamoui et al., 2011; Kraska et al., 2009; Nuzzo et al., 2008). The application of an appropriate filter or smoothing procedure would be expected to alter the characteristics of the original force signal, particularly its slope, and therefore has a considerable effect on the resulting RFD values, although this has yet to be tested. Finally, the determination of the starting force threshold that characterizes the beginning of the application of force during the isometric task is often not reported by the researchers (Haff et al., 1997; Kawamori et al., 2006; Khamoui et al., 2011; Kraska et al., 2009; Marcora and Miller, 2000). Given that the assessment of the isometric RFD involves rapidly rising force values, the

determination of the starting point is likely to have a significant effect on the resulting values. It is currently unclear how these different methodological factors affect the magnitude of the isometric force-time variables as well as their associated reliability. Therefore, the purposes of the present study were threefold: 1) to determine the inter-session reliability of force-time variables, 2) to use the reliability statistics to calculate the sample sizes and smallest worthwhile changes associated with the force-time variables, and 3) to investigate the effects of filter application and the starting force threshold on the force-time variables during an isometric back squat test.

Methods

In order to investigate the inter-session reliability of isometric force-time variables and the effects of filtering and the starting force threshold, eleven resistance-trained men attended three testing sessions during a three week period. Each participant's 1-repetition maximum (1-RM) parallel back squat was determined during the first session. The participants then attended two sessions where they performed tests of maximal isometric force development during a back squat task performed on force plates in order to calculate associated force-time variables. The force signal was processed differently to allow the effects of filtering and the starting force threshold selection to be determined.

Participants

Eleven resistance trained men (age: 22.5 ± 1.9 years; body mass: 90.3 ± 13.5 kg; body height: 1.82 ± 0.09; 1-RM parallel back squat: 147.3 ± 26.9 kg) volunteered to participate in this study which was approved by the institutional review board of the East Stroudsburg University of Pennsylvania. Each participant had a minimum of one year resistance training experience that included the back squat exercise in their workouts. Each participant signed an informed consent form prior to any testing.

Procedures

Each participant attended three testing sessions across a three week period, the first of which was used to determine their 1-RM load for the parallel back squat. During the remaining two sessions each participant performed the isometric back squat protocol. A minimum of one week was allowed between testing sessions and all tests were

conducted at the same time of day.

1-RM parallel back squat protocol. The 1-RM load achieved during the back squat exercise was determined using the protocol outlined by Baechle et al. (2008). The technique required the participants to lower the barbell to a depth where the anterior aspect of the thighs was parallel to the floor before raising it back to the starting position. The exercise was performed using an Olympic barbell and plates within a power rack.

Isometric back squat protocol. The isometric back squat test required the participants to stand on two force plates positioned within a squat-rack with their feet positioned slightly wider than shoulder-width apart. The barbell was locked in place at a height that permitted a 90° internal angle at the knee joint (Blazevich et al., 2002). The foot position and the height of the barbell were determined from a familiarization session performed by each participant following their 1-RM parallel back squat assessment during the first testing session. The foot position and barbell height were kept constant over the next two testing sessions for each participant.

All participants completed the same warm-up prior to each isometric testing session comprising dynamic activities for the lower-body (2 sets of 10 repetitions of the following exercises: bodyweight back squats, walking lunges, jumping jacks, high-knees). Each participant then performed a 3-s isometric squat at 50% of their perceived maximum effort, another at 80% of their perceived effort, and a final attempt at 100% of their perceived maximum effort with these repetitions being separated by a two minute rest period. Following further three minutes of rest the participants performed the first of their three 3-s trials at maximum effort.

Each participant was positioned under the barbell during the maximal effort trials with their feet in the correct position and they were instructed to remain stationary on the force plates with the superior aspect of their scapulae against the barbell (high bar position) grasping the barbell with a closed, pronated grip, and then to push against the barbell "as fast and as hard as possible" (Sahaly et al., 2001) and to keep pushing for 3 seconds once signaled (Andersen et al., 2010; Nuzzo et al., 2008). The experimenter provided a countdown to begin each trial and signaled when the 3 seconds had elapsed. The participants were verbally encouraged throughout each trial. Three trials were completed by each participant with a period of 3 min rest between the trials (Haff et al., 1997). Any trial where a participant performed a countermovement prior to beginning the trial was discarded and the participant was asked to repeat the trial following a rest period.

Calculation of Isometric Force-Time Variables

The isometric back squat protocol was performed with the participant standing on two force plates (Kistler Type 9286AA) sampling at a frequency of 1,200 Hz. The starting force threshold that defined the beginning of force application was defined in two ways: 1) when the vertical force trace first exceeded 1% of the participant's body mass (1% BM), 2) when the vertical force trace first exceeded 5% of the participant's body mass (5% BM), with body mass being calculated from a 1-s period when the participant stood stationary on the force plates prior to the beginning of the trial. Residual analysis performed on the raw force signal identified an optimal cut-off frequency of 19 Hz (Winter, 2009), and a low-pass, 4th order Butterworth filter was applied to the 1% BM data. There were then three data sets: 1) an unfiltered force signal with a 1% BM starting force threshold (1% BM unfiltered), 2) a filtered force signal with a 1% BM starting force threshold (1% BM filtered), 3) an unfiltered force signal with a 5% BM starting force threshold (5% BM unfiltered). Only one data set of the two different starting force thresholds was filtered as we considered the high frequency components (noise) that the filter was used to remove to be constant across the force signal within a given trial and not influenced by the magnitude of the force signal. Therefore, we did not expect the filter to produce any differential effects between the data derived from the two different starting force thresholds. Once body mass had been removed from the force signal the following force-time variables were calculated for all three data sets:

Maximal isometric force (F_{max}). The largest single value of vertical force achieved during the 3-s trial defined the maximal isometric force.

Time of maximal isometric force (Time F_{max}). The time from the beginning of the force application until the achievement of F_{max} defined the time of F_{max}.

Peak rate of force development (RFD_{peak}). The vertical force trace was differentiated using the first central difference method. The largest value of the

differentiated signal during the 3-s trial defined the peak rate of force development.

Time of peak rate of force development (Time RFD_peak). The time from the beginning of the force application until the achievement of the RFD_{peak} defined the time of RFD_{peak}.

Average rate of force development (RFD_ave). F_{max} was divided by Time F_{max} to provide the average rate of force development.

Rate of force development within specific time intervals. The vertical force trace was divided into 50 ms time periods from the start of the movement. Within each time period the force at that time was divided by the time to provide the rate of force development in 50, 100, 150, 200, 250, 500 and 1000 ms from the start of the movement (RFD_{50}, RFD_{100}, RFD_{150}, RFD_{200}, RFD_{250}, RFD_{500}, and RFD_{1000}, respectively).

The isometric force-time variables were averaged across the three trials performed during each of the two testing sessions prior to the statistical analyses.

Statistical Analysis

All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS version 18.0). Measures of the central tendency and spread of the data were represented as means and standard deviations. The reliability of the isometric force-time variables was determined by calculating the systematic bias, intraclass correlation coefficients (ICC) and coefficients of variation (CV). Systematic bias in the isometric force-time variables was determined by assessing the change in the mean between the two testing sessions using paired t-tests. Where systematic bias was identified, ICC and CV values were not calculated. The data were log-transformed prior to the calculation of ICC and CV values. Test-retest reliability of the force-time variables was calculated from a mixed-model (1,3) ICC (Morrow and Jackson, 1993). The within-subject variation was calculated as the CV for each variable and was derived from the typical error, as follows:

$$Typical\ error = \sqrt{MSE} \qquad (1)$$

where *MSE* is the mean square error value from a repeated measures ANOVA model. The CV was then calculated as:

$$CV = 100(e^{TE} - 1) \qquad (2)$$

where *TE* is the typical error. The 90% confidence limits (90% CL) were established for each of the variables (Hopkins, 2000a).

Differences in the isometric force-time variables caused by the application of the filter were determined using paired t-tests on the 1% BM unfiltered and 1% BM filtered data sets. The effects of the starting threshold on the isometric force-time variables were assessed using paired t-tests on the 1% BM unfiltered and the 5% BM unfiltered data sets. The alpha was corrected to $p \le 0.004$ for these analyses because of the number of comparisons.

Results

Figure 1 shows the mean force-time trace for all participants collected during the first testing session.

Tables 1, 2, and 3 show the data for the isometric force-time variables calculated for the 1% BM unfiltered, 1% BM filtered and 5% BM unfiltered conditions recorded during the two testing sessions, respectively.

Reliability

Systematic bias was not found for any of the isometric force-time variables under any of the conditions ($p > 0.004$). Tables 4 and 5 show the ICC and CV statistics, respectively, and the associated confidence limits for the isometric force-time variables.

The test-retest correlation value derived for a specific variable can be used to establish the number of participants required in a study where that variable is a dependent variable by using the following formula (Hopkins, 2000b):

$$Number\ of\ participants = 200 \times (1 - ICC) \qquad (3)$$

where *ICC* is the intraclass correlation coefficient for a given variable. It follows from the 1% BM unfiltered data collected during the first testing session in the present study that the use of isometric F_{max} derived from the isometric back squat protocol used herein would require 16 participants, while RFD_{200} as the dependent variable would require 26 participants. The use of the unreliable measure of RFD_{peak} produces the unsatisfactory requirement of 182 participants.

The practitioner could use the reliability

data presented here to calculate the smallest worthwhile change in a specific force-time variable. Following the recommendations of Hopkins (2000), a practitioner can use the CV data to determine the smallest worthwhile change in a given variable by using the following calculation:

$$Smallest\ worthwhile\ change = (present\ value \times TE^2) - present\ value$$
(4)

where TE is the ratio typical error ($[CV/100] + 1$). Using the 1% BM unfiltered data derived from session one in the present study, the smallest worthwhile change for F_{max} using the present isometric back squat protocol becomes ~122 N, while that for RFD_{50} becomes ~1561 N/s. Both RFD_{500} and RFD_{1000} produce smallest worthwhile changes of ~181 and ~116 N/s, respectively, rendering the RFD calculated over longer absolute time intervals as more sensitive measures.

The effects of filtering the force signal

The filtered value of F_{max} was significantly smaller than the value recorded from the unfiltered signal (mean difference: 3 N, $p < 0.004$; cf. Tables 1 and 2), while the filtered value of RFD_{peak} was also significantly smaller than that calculated from the unfiltered signal (mean difference: 3061 N/s; $p < 0.004$; cf. Tables 1 and 2). There were no other significant differences caused by the application of the filter ($p > 0.004$).

The effects of starting force threshold

The RFD values calculated using a starting force threshold of 5% BM were significantly greater than those calculated using the 1% BM starting force threshold for RFD_{50} (mean difference: 1230 N/s; $p < 0.004$), RFD_{100} (mean difference: 619 N/s; $p = 0.002$), RFD_{150} (mean difference: 326 N/s; $p = 0.001$), RFD_{200} (mean difference: 202 N/s; $p = 0.001$), RFD_{250} (mean difference: 110 N/s; $p = 0.003$) and RFD_{1000} (mean difference: 6 N/s; $p = 0.003$) (cf. Tables 1 and 3). There were no other significant differences caused by the different starting thresholds ($p > 0.004$).

Table 1

Maximal isometric force, time of maximal isometric force and rate of force development values calculated across the two testing sessions for the 1% BM unfiltered data condition.
Values are means ± standard deviations.

Force-time variable	Session 1	Session 2
F_{max} (N)	1219 ± 178	1183 ± 229
Time F_{max} (s)	2.11 ± 0.38	2.11 ± 0.58
RFD_{peak} (N/s)	9430 ± 2891	7396 ± 2357
Time RFD_{peak} (s)	0.20 ± 0.28	0.18 ± 0.30
RFD_{ave} (N/s)	591 ± 112	622 ± 267
RFD_{50} (N/s)	3667 ± 2025	3615 ± 2624
RFD_{100} (N/s)	3813 ± 1768	3452 ± 1947
RFD_{150} (N/s)	3551 ± 1334	3147 ± 1388
RFD_{200} (N/s)	3330 ± 942	2848 ± 1043
RFD_{250} (N/s)	3070 ± 832	2647 ± 844
RFD_{500} (N/s)	1925 ± 387	1675 ± 471
RFD_{1000} (N/s)	1029 ± 231	1010 ± 333

F_{max} = the maximal force achieved during the 3 s period; Time F_{max} = the time from the start of force application to that when maximal force is achieved; RFD_{peak} = peak rate of force development; Time RFD_{peak} = the time from the start of force application to that when RFD_{peak} is achieved; RFD_{ave} = average rate of force development; RFD_{50} = rate of force development in the first 50 ms; RFD_{100} = rate of force development in the first 100 ms; RFD_{150} = rate of force development in the first 150 ms; RFD_{200} = rate of force development in the first 200 ms; RFD_{250} = rate of force development in the first 250 ms; RFD_{500} = rate of force development in the first 500 ms; RFD_{1000} = rate of force development in the first 1000 ms.

Table 2

Maximal isometric force, time of maximal isometric force and rate of force development values calculated across the two testing sessions for the 1% BM filtered data condition. Values are means ± standard deviations.

Force-time variable	Session 1	Session 2
F_{max} (N)	1217 ± 179*	1180 ± 229
Time F_{max} (s)	2.10 ± 0.36	2.09 ± 0.60
RFD_{peak} (N/s)	6369 ± 1509*	5270 ± 2280
Time RFD_{peak} (s)	0.09 ± 0.06	0.09 ± 0.06
RFD_{ave} (N/s)	592 ± 111	632 ± 273
RFD_{50} (N/s)	3773 ± 2077	3755 ± 2584
RFD_{100} (N/s)	3859 ± 1805	3544 ± 1943
RFD_{150} (N/s)	3553 ± 1365	3179 ± 1394
RFD_{200} (N/s)	3341 ± 961	2872 ± 1050
RFD_{250} (N/s)	3078 ± 845	2664 ± 848
RFD_{500} (N/s)	1925 ± 388	1677 ± 471
RFD_{1000} (N/s)	1030 ± 232	1012 ± 333

F_{max} = the maximal force achieved during the 3 s period; Time F_{max} = the time from the start of force application to that when maximal force is achieved; RFD_{peak} = peak rate of force development; Time RFD_{peak} = the time from the start of force application to that when RFD_{peak} is achieved; RFD_{ave} = average rate of force development; RFD_{50} = rate of force development in the first 50 ms; RFD_{100} = rate of force development in the first 100 ms; RFD_{150} = rate of force development in the first 150 ms; RFD_{200} = rate of force development in the first 200 ms; RFD_{250} = rate of force development in the first 250 ms; RFD_{500} = rate of force development in the first 500 ms; RFD_{1000} = rate of force development in the first 1000 ms.
* Significantly different from 1% BM unfiltered (p < 0.004).

Table 3

Maximal isometric force, time of maximal isometric force and rate of force development values calculated across the two testing sessions for the 5% BM unfiltered data condition. Values are means ± standard deviations.

Force-time variable	Session 1	Session 2
F_{max} (N)	1219 ± 178	1183 ± 229
Time F_{max} (s)	2.10 ± 0.38	2.09 ± 0.57
RFD_{peak} (N/s)	9430 ± 2891	7396 ± 2357
Time RFD_{peak} (s)	0.18 ± 0.28	0.16 ± 0.29
RFD_{ave} (N/s)	595 ± 112	629 ± 269
RFD_{50} (N/s)	4897 ± 2159†	4707 ± 2546
RFD_{100} (N/s)	4432 ± 1706†	3867 ± 1843
RFD_{150} (N/s)	3877 ± 1286†	3420 ± 1313
RFD_{200} (N/s)	3532 ± 899†	3052 ± 979
RFD_{250} (N/s)	3180 ± 826†	2777 ± 914
RFD_{500} (N/s)	1937 ± 381	1689 ± 470
RFD_{1000} (N/s)	1035 ± 229†	1017 ± 341

F_{max} = the maximal force achieved during the 3 s period; Time F_{max} = the time from the start of force application to that when maximal force is achieved; RFD_{peak} = peak rate of force development; Time RFD_{peak} = the time from the start of force application to that when RFD_{peak} is achieved; RFD_{ave} = average rate of force development; RFD_{50} = rate of force development in the first 50 ms; RFD_{100} = rate of force development in the first 100 ms; RFD_{150} = rate of force development in the first 150 ms; RFD_{200} = rate of force development in the first 200 ms; RFD_{250} = rate of force development in the first 250 ms; RFD_{500} = rate of force development in the first 500 ms; RFD_{1000} = rate of force development in the first 1000 ms.
† Significantly different from 1% BM unfiltered (p < 0.004).

Intraclass correlation coefficients and the 90% confidence limits for the measures of maximal isometric force, time of maximal isometric force and the absolute measures of isometric rate of force development calculated across the two testing sessions for the 1% BM unfiltered, the 1% BM filtered, and the 5% BM unfiltered data conditions.

	1% BM unfiltered		1% BM filtered		5% BM unfiltered	
	ICC	90% CL	ICC	90% CL	ICC	90% CL
F_{max} (N)	0.92	0.76–0.97	0.92	0.76-0.97	0.92	0.76–0.97
Time F_{max} (s)	0.03	-0.55-0.60	0.00	-0.52-0.52	0.67	0.23-0.88
RFD_{peak} (N/s)	0.09	-0.46-0.59	0.36	-0.20-0.74	0.09	-0.46-0.59
Time RFD_{peak} (s)	0.42	-0.13-0.77	0.36	-0.20-0.74	0.40	-0.16-0.76
RFD_{ave} (N/s)	0.05	-0.49-0.56	0.02	-0.51-0.54	0.65	0.19-0.88
RFD_{50} (N/s)	0.96	0.88-0.99	0.96	0.88-0.99	0.91	0.74-0.97
RFD_{100} (N/s)	0.93	0.79-0.98	0.93	0.79-0.98	0.91	0.74-0.97
RFD_{150} (N/s)	0.92	0.76-0.97	0.92	0.76-0.97	0.93	0.79-0.98
RFD_{200} (N/s)	0.87	0.64-0.96	0.87	0.64-0.96	0.88	0.66-0.96
RFD_{250} (N/s)	0.88	0.66-0.96	0.88	0.66-0.96	0.89	0.69-0.96
RFD_{500} (N/s)	0.95	0.85-0.98	0.95	0.85-0.98	0.95	0.85-0.98
RFD_{1000} (N/s)	0.92	0.76-0.97	0.92	0.76-0.97	0.92	0.76-0.97

1% BM unfiltered = variables calculated from the unfiltered force signal with a start threshold of 1% of body mass; 1% BM filtered = variables calculated from the filtered force signal with a start threshold of 1% of body mass; 5% BM unfiltered = variables calculated from the unfiltered force signal with a start threshold of 5% of body mass; 90% CL = 90% confidence limits; F_{max} = the maximal force achieved during the 3-s period; Time F_{max} = the time from the start of force application to that when maximal force is achieved; RFD_{peak} = peak rate of force development; Time RFD_{peak} = the time from the start of force application to that when RFD_{peak} is achieved; RFD_{ave} = average rate of force development; RFD_{50} = rate of force development in the first 50 ms; RFD_{100} = rate of force development in the first 100 ms; RFD_{150} = rate of force development in the first 150 ms; RFD_{200} = rate of force development in the first 200 ms; RFD_{250} = rate of force development in the first 250 ms; RFD_{500} = rate of force development in the first 500 ms; RFD_{1000} = rate of force development in the first 1000 ms.

Table 5

Coefficients of variation and the 90% confidence limits for the measures of maximal isometric force, time of maximal isometric force and the absolute measures of isometric rate of force development calculated across the two testing sessions for the 1% BM unfiltered, the 1% BM filtered, and the 5% BM unfiltered data conditions.

	1% BW unfiltered		1% BW filtered		5% BW unfiltered	
	CV (%)	90% CL	CV (%)	90% CL	CV (%)	90% CL
F_{max} (N)	4.9	3.6-7.8	4.9	3.6-7.8	4.9	3.6-7.8
Time F_{max} (s)	52.5	38.8-83.6	53.0	39.1-84.4	34.7	25.7-55.3
RFD_{peak} (N/s)	36.5	27.0-58.2	26.5	19.6-42.2	36.5	27.0-58.2
Time RFD_{peak} (s)	139	103-221	26.5	19.6-42.2	168	124-268
RFD_{ave} (N/s)	52.8	39.0-84.1	53.4	39.5-85.1	35.4	26.2-56.4
RFD_{50} (N/s)	19.4	14.3-30.9	19.3	14.3-30.8	16.9	12.5-26.9
RFD_{100} (N/s)	18.1	13.4-28.8	18.0	13.3-28.7	18.5	13.7-29.5
RFD_{150} (N/s)	16.6	12.3-26.4	16.6	12.3-26.4	13.8	10.2-22.0
RFD_{200} (N/s)	18.1	13.4-28.8	18.0	13.3-28.7	13.5	10.0-21.5
RFD_{250} (N/s)	14.1	10.4-22.5	14.2	10.5-22.6	13.0	9.6-20.7
RFD_{500} (N/s)	4.6	3.4-7.3	4.6	3.4-7.3	4.1	3.0-6.5
RFD_{1000} (N/s)	5.5	4.1-8.8	5.5	4.1-8.8	5.4	4.0-8.6

*1% BM unfiltered = variables calculated from the unfiltered force signal with a start threshold
of 1% of body mass; 1% BM filtered = variables calculated from the filtered force signal with
a start threshold of 1% of body mass; 5% BM unfiltered = variables calculated from the unfiltered
force signal with a start threshold of 5% of body mass; 90% CL = 90% confidence limits;
F_{max} = the maximal force achieved during the 3-s period;
Time F_{max} = the time from the start of force application to that when maximal force is achieved;
RFD_{peak} = peak rate of force development;
Time RFD_{peak} = the time from the start of force application to that when RFD_{peak} is achieved;
RFD_{ave} = average rate of force development; RFD_{50} = rate of force development in the first 50 ms;
RFD_{100} = rate of force development in the first 100 ms;
RFD_{150} = rate of force development in the first 150 ms;
RFD_{200} = rate of force development in the first 200 ms;
RFD_{250} = rate of force development in the first 250 ms;
RFD_{500} = rate of force development in the first 500 ms;
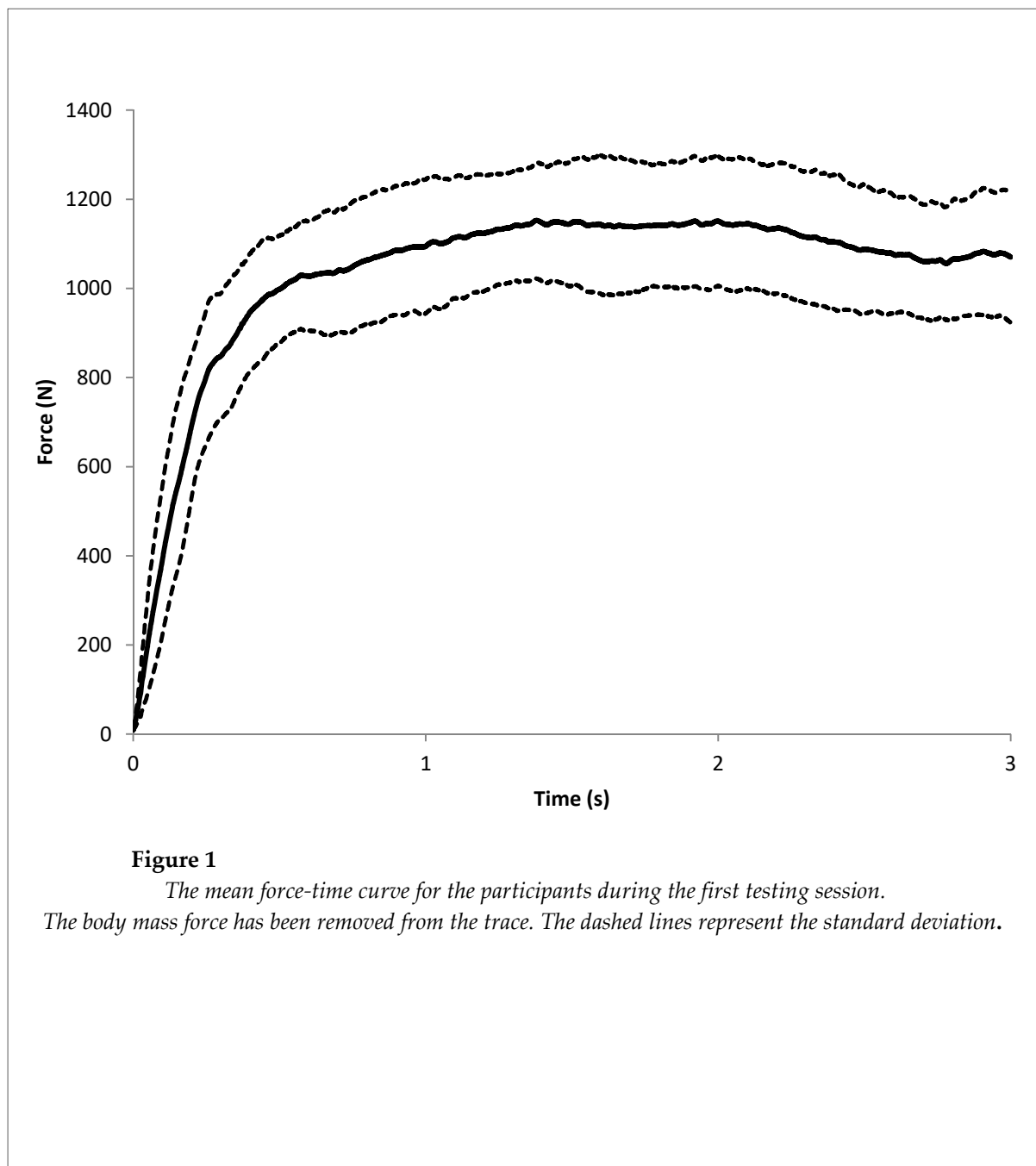RFD_{1000} = rate of force development in the first 1000 ms.*

Figure 1
The mean force-time curve for the participants during the first testing session.
The body mass force has been removed from the trace. The dashed lines represent the standard deviation.

Discussion

The first aim of the present study was to determine the inter-session reliability of force-time variables during an isometric squat task. There was no systematic bias reported for any of the force-time variables in the present study, implying that familiarization sessions are not required when using the current testing protocol with resistance-trained men. The force-time variables of Time F_{max}, RFD_{peak}, Time RFD_{peak}, and RFD_{ave} all demonstrated

poor reliability (ICC < 0.80; CV > 26%). There was a large difference in the reliability of F_{max} compared to Time F_{max} in the present study (Tables 4 and 5). McLellan et al. (2011) reported that Time F_{max} was slightly less reliable than F_{max} in vertical jumps, although the difference was not as large as that reported here for the two variables. It is possible that the poor reliability of Time F_{max} in the present study is due to the extended time period for force production in the isometric back squat protocol (3 s) compared to that associated with vertical jump

performance (< 1 s). The poor reliability of Time F_{max} in the present study also contributed to that associated with the measures of RFD_{ave} (Tables 4 and 5).

The measure of the RFD_{peak} is determined by the maximal instantaneous slope of the force-time trace and will be influenced by external sources of noise (i.e. vibrations transmitted to the force plates). The possible influence of external vibrations on the reliability of this measure can be observed by the improvement in the reliability statistics on the filtered force-time signal (Tables 4 and 5). The influence of external vibrations contaminating the force-time trace is an important consideration given that the force plates used in the present study were portable and laid on the surface of the laboratory floor, increasing the likelihood of noise from external vibrations being detected by the transducers within the force plates. Although the inter-session reliability of the RFD_{peak} during an isometric back squat procedure has not been reported previously, other authors have reported poor reliability for this measure during vertical jump performance (Moir et al., 2009). It is apparent from the present study data that the reliability of the RFD calculated within specific time intervals (e.g. RFD_{50}, RFD_{100}, etc.) greatly exceeds that of either the RFD_{peak} or RFD_{ave} during an isometric back squat test in resistance-trained men. However, it is currently unclear how the type of the force plate affects measures such as RFD_{peak} during isometric tasks.

Despite the acceptable test-retest statistics reported for F_{max} and the measures of the RFD calculated within specific time intervals in the present study, the within-subject variation for these measures varied considerably (CV: 4.1 – 19.4%. Table 5). The within-subject variation for F_{max} in the present study was slightly higher than that reported previously by Blazevich et al. (2002) using a similar isometric back squat protocol (CV: ~1%). However, no previous researchers have investigated the inter-session reliability of the RFD calculated across specific time intervals in an isometric back squat protocol. The within-subject variation tended to be greater for the RFD calculated across the shorter compared to the longer time intervals (cf. CV for RFD_{50} with that for RFD_{1000} in Table 5). The improved reliability at longer time intervals may be due to the difference in the signal-to-noise ratio in the force signal on the different regions of the force-time trace. Specifically, assuming a constant level of noise in the signal, the lower forces associated with the RFD calculated over the smaller absolute time intervals would mean that the recorded force trace contains a greater proportion of noise, increasing the variability of the measure. However, others have reported that the early phase of the voluntary RFD is characterized by very high inter-individual variation compared to the late phases of the RFD (Folland et al., 2014). These authors proposed that the variability early during the voluntary contractions was due to the integrated contribution of neural drive (evidenced by the magnitude of agonist EMG) and intrinsic properties of the active muscles (twitch force). It is possible that the pronounced within-subject variability during the early phase of the RFD may reflect the variability associated with the intrinsic properties of the neuromuscular system. As such, our findings may be specific to sample of resistance-trained men recruited for the study and so future researchers should investigate the influence of intrinsic neuromuscular properties on the reliability of force-time measures during isometric tasks.

Another aim of the present study was to determine the effects of filter application and the starting force threshold on the magnitude and reliability of the force-time variables. Filters are used to attenuate specific frequency components within signals and reduce the impact of noise (Winter, 2009). The application of a filter to the force-time trace could be expected to alter the variables influenced by noise such as instantaneous peak values and those determined by rates of change in force. The use of a filter resulted in significantly smaller values of F_{max} and RFD_{peak}. However, the magnitude of the differences in these variables (< 1% and ~26%) was within the associated CV values. Furthermore, the application of the filter had a negligible effect on the reliability of force-time variables, with the exception of the RFD_{peak} and Time RFD_{peak}. However, both RFD_{peak} and Time RFD_{peak} still demonstrated poor reliability after filtering. Therefore, it would appear unnecessary to filter the force-time data prior to the calculation of the most reliable force-time variables (F_{max}, RFD within specific time intervals).

The use of different percentages of body mass in determining the start of the rise in the force

trace did have an effect on the force-time variables. Specifically, the RFD values calculated in absolute time periods using a starting force threshold of 5% BM were significantly greater than those calculated using the 1% BM starting threshold (cf. Tables 1 and 3). Although it is not clear from Figure 1, the force-time trace during an isometric back squat is sigmoidal, as it is in isolated animal muscle (Edman and Josephson, 2007). Some of the early phase of the rise in force is likely to be absent when the starting force threshold is 5% BM which would therefore remove the initial region of low force development, leaving regions of the force trace comprising greater slopes, given that the magnitude of the slope of the rising force trace decreases as the athlete approaches F_{max}. Indeed, the magnitude of the difference between the RFD variables calculated when the starting force threshold of 1% BM is compared to 5% BM was largest for RFD_{50} (~34%) and decreased as the duration of calculation increased, being smallest for RFD_{1000} (< 1%). The use of a 5% BM starting force threshold resulted in a slight increase in the reliability for most of the force-time variables (particularly CV). However, the 5% BM starting threshold shifted the force-time curve by approximately 100 ms compared to the use of the 1% BM threshold (cf. Time F_{max} of 1% BM and 5% BM in Table 1). This temporal shift to a later start in the force-time signal when using the 5% BM starting force threshold would therefore preclude the analysis of the early phase of the RFD that has been identified by previous researchers (Andersen and Aagaard, 2006). Therefore, we recommend the use of the 1% BM starting force threshold when using the isometric back squat protocol presented here.

In conclusion, the ICC and CV for force-time variables recorded during an isometric back squat test ranged from 0.03 to 0.96 and 4.6 to 168%, respectively. The application of a low-pass filter significantly reduced the magnitude of certain force-time variables (F_{max}, RFD_{peak}) and increased the reliability of others (RFD_{peak}, Time RFD_{peak}), although the reliability of these variables was still poor. The calculation of the RFD during specific time intervals (50 – 1000 ms) is recommended. The use of a 5% BM starting force threshold increased the magnitude of many of the RFD measures and resulted in slight improvements in the reliability of many of these measures. However, the use of a 5% BM starting force threshold would preclude the assessment of the early phase of the RFD and therefore a 1% BM starting force threshold without a filter is recommended when using the isometric back squat protocol presented here.

Practical Implications

Isometric tests of strength allow the measurement of maximal strength (peak force) as well as explosive strength (RFD) during tasks that have been proposed to require less skill, take less time to administer, and potentially involve less muscle damage. The isometric back squat protocol used in the present study involves an exercise that most resistance-trained athletes are familiar with but does require that the practitioner have access to force plates in order to measure the force-time characteristics. However, with access to suitable force plates the practitioner can determine reliable measures of peak isometric force and the RFD assessed during 50 ms time intervals when using a starting threshold of 1% BM without the requirement of filtering the force-time signal. The data from the present study can then be used to establish the smallest worthwhile changes in the specific force-time variables, allowing practitioners to monitor their athletes during a period of training, and to determine the required sample sizes when developing research studies in which the specific force-time variables of peak isometric force and RFD are dependent variables.

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