ISSN 2703—240X

The Journal of Sport & Exercise Science™

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SPORT & EXERCISE SCIENCE
NEW ZEALAND

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The Journal of Sport and Exercise Science, Vol. 9, Issue 1, 1-11 (2025)

www.jses.net

JSES

ISSN: 2703-240X

The relationship between force measures from isometric first and isometric mid-thigh pull with weightlifting performance across 16 weeks

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ARTICLE INFO

Received: 17.09.2024
Accepted: 08.11.2024
Online: 18.04.2025

Keywords:
Peak force
Rate of force development
Snatch
Clean

ABSTRACT

The aim of this study was to determine the relationship between snatch and clean performance with force-time characteristics obtained from isometric first (IFP) and isometric mid-thigh pull (IMTP) over several mesocycles. Ten male and female weightlifters (age: 27.4 ± 1.9 years, body mass: 69.8 ± 113.2 kg, height: 1.67 ± 0.08 m) from the national training squad performed the IFP, IMTP, and 85% of season's best for snatch and clean on three separate occasions each separated by eight weeks. Near perfect correlations were observed between IFP and IMTP peak force (PF) with snatch and clean peak power (PP) and mean power (MP) on week 0, 8, and 16 (r = 0.954 – 0.991, p < 0.001). Very large – near perfect correlations were observed between IFP force at 200 ms ($Force_{200}$) and IFP rate of force development at 200 and 250 ms ($RFD_{0\text{-}200}$ and $RFD_{0\text{-}250}$, respectively) with snatch and clean PP and MP at week 0 (r = 0.753 – 0.847, p = 0.008 – 0.048). Very large – near perfect correlations were observed between IFP $Force_{50}$ and $Force_{200}$ with snatch and clean PP and MP at week 8 and 16 (r = 0.777 – 0.865, p = 0.004 – 0.032). Very large correlations were also observed between IFP $RFD_{0\text{-}200}$ and $RFD_{0\text{-}250}$ with clean PP and MP at week 16 (r = 0.752 – 0.778, p = 0.032 – 0.048). The results indicate the importance of maximum force capabilities at both first and second pull positions, and early force development and RFD at first pull position for weightlifting performance.

1. Introduction

Weightlifting is a sport which requires athletes to lift as much weight as possible, overhead, in the snatch (SN) and the clean (CN) and jerk events. To succeed, athletes are required to possess the ability to generate a high level of force rapidly (Chavda et al., 2023; Fry et al., 2006; Sorenson et al., 2022). For example, it was reported that the ability to generate large extensor muscle joint impulse (force × time) is an important factor in lifting heavier loads during the clean (Kipp & Harris, 2017). In addition, Haff et al. (2005) reported a high correlation (r = 0.80) between rate of force development (RFD) during the isometric mid-thigh pull (IMTP) with weightlifting total (sum of best snatch and clean and jerk) weight in elite female weightlifters. Furthermore, Sorenson et al. (2022) reported that the average resultant force of the weighting phase (first pull: the lifting of the barbell from the floor to about mid-thigh position) and average bar power from the point of lift off to peak bar height showed high correlations ($r \geq$ 0.88) to weightlifting performance. In view of the strong relationship between force generation capability and weightlifting performance, it is therefore important to monitor the muscular strength of weightlifters, for coaches to better plan and evaluate their training program.

Isometric strength assessments have been gaining popularity as they are relatively simple to administer, pose minimal injury risk, have high test-retest reliability (Brady et al., 2020; Lum et al., 2020), are able to detect subtle changes in strength (e.g., change in RFD and early force development; Drake et al., 2018), and are considered less fatiguing than 1 repetition maximum (1RM) tests (Lum et al., 2020). Specifically, measures obtained from the IMTP, which requires the athlete to exert force against a

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fixed bar while adopting the second pull position (the upward extension of the body to accelerate and elevate the barbell from about mid-thigh to the full extended position) of the clean, has been reported to be highly correlated to weightlifting performance (r = 0.80 – 0.91) (Beckham et al., 2013; Ben-Zeev et al., 2022; Haff et al., 2005; Joffe et al., 2021). Significant correlations between IMTP RFD, early force development, and weightlifting performance has also been observed (r = 0.65 – 0.80; Beckham et al., 2013). Based on these findings, weightlifting coaches may use IMTP as an assessment tool to monitor the force generation capability of their athletes to monitor adaptations to training.

While the IMTP is a feasible option for monitoring weightlifting athletes, Ben-Zeev et al. (2022) and Joffe et al. (2021) reported higher correlations (r = 0.81 – 0.96) between isometric force and weightlifting performance when isometric peak force was obtained from the first pull position of clean (IFP) as compared to IMTP (r = 0.60 – 0.91). These findings support the suggestion that isometric force has a stronger relationship with a dynamic movement when the test is performed in the position where concentric force is initiated for that movement (Lum et al., 2020). Hence, this finding suggests that IFP serves as another option for weightlifting coaches to use for monitoring their athletes. However, despite the findings by Ben-Zeev et al. (2022) and Joffe et al. (2021), only Ben-Zeev et al. (2022) compared the relationship between RFD and early force development obtained from the IFP and IMTP with weightlifting performance. As rapid force production obtained during the IMTP (e.g., RFD and force at early time-points [i.e., 100-, 150-, 200-, 250-ms)]) has previously found to be an important determinant of weightlifting performance (Beckham et al., 2013; Haff et al., 2005), and there is a lack of data on rapid force development obtained from IFP, this warrants further investigation.

Although researchers have shown high correlation between weightlifting performance with measures of IFP and IMTP (Beckham et al., 2013; Ben-Zeev et al., 2022; Haff et al., 2005; Joffe et al., 2021), the researchers did not perform long-term monitoring of weightlifters' performance using these two isometric strength assessments. Considering that the changes in dynamic and isometric strength performance were shown to be disproportional (James et al., 2023), it is likely that the correlation between weightlifting performance with measures of IFP and IMTP would change over time. Indeed, results from a previous study showed that the relationship between isometric strength measures and dynamic movement performance may change after a period of training (Lum & Joseph, 2020). This outcome may also be observed for the relationship between weightlifting performance measures with IFP and IMTP measures, hence, altering the ability of IFP and IMTP force-time characteristics in predicting weightlifting performance. In view of this, the purpose of the study was to determine the relationship between weightlifting performance with force-time characteristics obtained from IFP and IMTP over several mesocycles. In line with previous findings, it was hypothesized that (1) weightlifting performance, as determined by the mean power and peak power during SN and CN at 85% of season best, would demonstrate stronger correlations with RFD and early force development obtained from IFP than IMTP; and (2) the relationship between weightlifting performance with measures obtained from IFP and IMTP will be affected by the training that athletes undergo during each mesocycle.

2. Methods

An observational repeated measures design was used to determine the relationships between the force-time characteristics of the IFP and IMTP with weightlifting performance including competition best snatch (SN) and clean (CN) at week 0, and peak power and mean power at 85% best SN and CN (based on their best clean and jerk load) in national male and female weightlifters over a period of 16 weeks. For each testing session, participants performed the IFP, IMTP, and SN and CN at 85% of their competition best. This intensity was selected to minimize any disruption to athletes' training as they trained within this intensity most of the time. Participants performed three testing sessions in total at week 0, 8, and 16.

2.1. Participants

A convenience sample of six male (age: 28.7 ± 2.0 years, body mass: 73.2 ± 11.4 kg, height: 1.72 ± 0.05 m) and four female (age: 26.0 ± 1.4 years, body mass: 57.5 ± 3.7, height: 1.61 ± 0.04 m) weightlifters from the national training squad were recruited for this study. Inclusion criteria included: (1) 18 – 35 years old; (2) had been participating in competitive weightlifting for more than 2 years; (3) is currently in the national training squad; and (4) was free from injury at the point of recruitment. Study commenced after obtaining the approval from the institutional review board of the Singapore Sport Institute (SC-EXP-029). All participants were briefed on the procedure of the study and signed an informed consent form.

2.2. Procedure

Participants were asked to avoid the consumption of heavy meals 2 hours before each testing session. All testing sessions were conducted at similar time between sessions (within 1 hour) to avoid diurnal effect. To ensure that participants were able to perform at their best during each session, participants performed their individual competition warm up regime during each session. Participants performed the tests in the following order each separated by 5 minutes, IFP, IMTP, SN, and CN.

2.3. Isometric strength tests

Both IFP and IMTP were performed on the dual force plates (Force Decks, VALD Performance, FD4000, Queensland, Australia) sampling at 1000 Hz. The commercially available ForceDecks software (VALD Performance, ForceDecks, Queensland, Australia) was used to analyze all force-time data obtained during the tests, using raw unfiltered data. For the IFP, participants were asked to adopt a posture that reflected the start of the first pull of a clean (Figure 1A). The bar height (22.2 cm off the ground) was based on the height of a weightlifting bar when loaded with standard weightlifting weight plates of 45 cm in diameter. Therefore, the body position of each participant varied slightly due to individual anthropometric and mobility characteristics. However, key technical criteria of the set-up position for the clean was followed (Joffe et al., 2021). This was visually inspected by the weightlifting coach prior to the commencement of the test. For the IMTP, participants adopted a posture that reflects the start of the second pull of the clean resulting in a knee flexion angle of 125 – 145˚, and hip flexion angle of 140 – 150˚ (Comfort et al., 2019) (Figure 1B). A handheld goniometer was used to ensure that athletes adopt the required knee and hip angles and that these were replicated across testing sessions. For both tests, participants were required to hold on to the bar with elbows fully extended, using lifting straps to ensure that grip strength was not a limiting factor. Prior to each test, participants performed a 3 s submaximal IFP or IMTP at 50%, 70%, and 90% perceived maximal effort. Each repetition was separated by 60 s (Comfort et al., 2019).

Figure 1: Posture adopted for (A) isometric first pull, and (B) isometric mid-thigh pull.

During the test, participants were asked to drive their feet into the ground "as fast and as hard possible" following a "3, 2, 1 pull" countdown from the tester. During the first two attempts, participants maintained the tension for a period of 1 s with each repetition separated by 20 s (Guppy et al., 2022). Force at 100, 150, and 200 ms ($Force_{100}$, $Force_{150}$, and $Force_{200}$, respectively) and mean rate of force development at 0-100, 0-150, 0-200 and 0-250 ms (RFD_{0-100}, RFD_{0-150}, RFD_{0-200} and RFD_{0-250}, respectively) from the onset of pull were determined for each trial. The average of the two trials were recorded and analyzed. Participants rested for 2 minutes before performing 2 more attempts in which they maintained the tension for a period of 5 s with acceptable trials demonstrating no countermovement and peak force between trials demonstrating a difference < 250 N. Each repetition was separated by 2 minutes (Comfort et al., 2019). The average of the peak force generated by the two trials was recorded and analyzed. The onset of pull was determined based on an increase of > 5 standard deviation (SD) of participants body mass during a period of quiet standing prior to the pull (Dos' Santos et al., 2017). This setting is available in the ForceDecks software. A 20 kg stiff powerlifting barbell (Eleiko, Sweden) was used for all testing. The barbell was loaded with sufficient weight plates to ensure that participants were not able to move the bar.

2.4. Snatch and clean

The SN and CN performance were determined as the mean power (MP) and peak power (PP) obtained when lifting 85% of individual's season's best. The reason for using the using the submaximal load is firstly, to avoid disruption to participants' training, and the 85% load is a commonly used load during training. Secondly, assessing power output is suggested to be a good predictor of weightlifting performance (Garhammer, 1980; Garhammer, 1993). Specifically in the current study where the weight lifted was kept constant throughout the 16-week period, a higher power measured would indicate an improvement in performance. This would allow the athletes to be aware of their progression without the need to perform a maximal lift. During the SN and CN, participants began their build up to 85% of their season's best by performing 3 repetitions at 40% and 50%, 2 repetitions at 60% and 70%, and 1 repetition at 80% of their season's best. Each repetition was separated by 30 s and each load intensity by 3 min. Participants performed the 85% for two attempts, each separated by 3 min. A linear position transducer (LPT; GymAware, Kinetic Performance Technology, Canberra, Australia) was used to determine the peak and mean velocity of the barbell. The mean and peak power was determined as the instantaneous product between the net force applied to the barbell (i.e., barbell mass × vertical barbell acceleration, based on the displacement time data from the LPT) and vertical barbell mean and peak velocity. The average of both attempts was used for further analysis. Participants lifted the same testing load for SN and CN during subsequent testing sessions.

2.5. Statistical analyses

Statistical analysis was performed using the JASP version 0.18.3.0. All tested variables were expressed by Mean (± 1 SD). Within session test-retest reliability was assessed using two-way, mixed intraclass correlation coefficients (ICC) and coefficient of variation (%CV) for all measured variables. ICC values were deemed as poor, moderate, good, or excellent if lower bound 95% confidence interval (CI) of ICC values were < 0.50, 0.50 – 0.74, 0.75 – 0.90, or > 0.90, respectively (Koo & Li, 2016). Acceptable within-session variability was classified as ≤ 10% (Cormack et al., 2008). All assumptions to run ANOVA were checked beforehand, including normality and sphericity. A one-way ANOVA with Tukey post-hoc analysis was used to determine the differences in all variables measured at different time points ($p \leq 0.05$). To reduce the incidence of bias due to the small sample size, Hedges' g was computed, where the following descriptors were used: (i) trivial effect size if $g < 0.20$; (ii) small effect size if $g = 0.20 – 0.49$; (iii) moderate effect size if $g = 0.50 – 0.80$; and (iv) large effect size if $g > 0.80$ (Cohen, 1988).

Pearson correlation coefficients (r) and the associated 95% CI was used to determine the interrelationships among isometric assessment and weightlifting performance measures. The strength of all correlations was interpreted using the following criteria: trivial (< 0.10), small (0.10 – 0.29), moderate (0.30 – 0.49), large (0.50 – 0.69), very large (0.70 – 0.90), or near perfect (> 0.90) (Hopkins et al., 2009). Fisher r-z transformation was performed to compare the magnitude of correlation between isometric assessment and weightlifting performance measures at different time points (Raghunathan et al., 1996). An a priori alpha level was set at $p < 0.05$, and p-values associated with the correlations were subsequently adjusted for familywise error rates, based on the multiple correlations (adjusted $p = p \div 4$).

3. Results

The reliability analysis of all measured variables is displayed in Table 1. Excellent reliability was observed for MP and PP obtained from SN and CN, as well as PF obtained from IFP and IMTP (ICC = 0.977 – 0.997, 95% CI = 0.933 – 1.00, %CV = 1.1 – 3.7, 95% CI = 0.9 – 5.2). Good reliability was observed for IFP $Force_{50}$, $Force_{200}$, RFD_{0-200}, and RFD_{0-250}, and IMTP $Force_{50}$, $Force_{150}$, RFD_{0-200}, and RFD_{0-250} (ICC = 0.852 – 0.939, 95% CI = 0.750 – 0.968, %CV = 5.2 – 7.1, 95% CI = 4.1 – 8.8). Moderate reliability was observed for IFP $Force_{100}$ and $Force_{150}$, and IMTP $Force_{100}$ and $Force_{200}$ (ICC = 0.783 – 0.847, 95% CI = 0.645 – 0.918, %CV = 4.7 – 6.9, 95% CI = 3.7 – 9.6). The IFP and IMTP RFD_{0-50}, RFD_{0-100}, and RFD_{0-150} showed unacceptable %CV (ICC = 0.686 – 0.850, 95% CI = 0.509 – 0.919, %CV = 11.6 – 19.7, 95% CI = 9.0 – 28.3).

Table 1: Reliability analysis of snatch, clean, and isometric force measures.

	ICC	95% CI	%CV	95% CI
Snatch				
Peak power	**0.998**	**[0.995, 1.000]**	**1.1**	**[0.9, 1.5]**
Mean power	**0.984**	**[0.958, 0.995]**	**1.8**	**[1.4, 2.5]**
Clean				
Peak power	**0.992**	**[0.969, 0.998]**	**1.7**	**[1.3, 2.3]**
Mean power	**0.995**	**[0.982, 0.999]**	**2.1**	**[1.7, 2.9]**
IFP				
Peak force	**0.977**	**[0.933, 0.994]**	**3.7**	**[2.9, 5.2]**
$Force_{50}$	**0.867**	**[0.774, 0.929**	**6.3**	**[4.9, 8.8]**
$Force_{100}$	0.847	[0.742, 0.918]	6.0	[4.7, 8.4]
$Force_{150}$	0.791	[0.656, 0.886]	6.6	[5.2, 9.3]
$Force_{200}$	**0.852**	**[0.750, 0.921]**	**5.2**	**[4.1, 7.3]**
RFD_{0-50}	0.730	[0.569, 0.849]	12.9	[10.1, 18.3]
RFD_{0-100}	0.801	[0.672, 0.892]	19.7	[15.3, 28.3]
RFD_{0-150}	0.750	[0.598, 0.861]	12.3	[9.6, 17.5]
RFD_{0-200}	**0.869**	**[0.776, 0.930]**	**6.8**	**[5.4, 9.6]**
RFD_{0-250}	**0.902**	**[0.829, 0.948]**	**6.5**	**[5.1, 9.0]**
IMTP				
Peak force	**0.997**	**[0.995, 0.999]**	**1.1**	**[0.9, 1.5]**
$Force_{50}$	**0.902**	**[0.829, 0.948]**	**5.3**	**[4.2, 7.4]**
$Force_{100}$	0.783	[0.645, 0.881]	6.9	[5.4, 9.6]
$Force_{150}$	**0.865**	**[0.770, 0.928]**	**6.3**	**[4.9, 8.8]**
$Force_{200}$	0.842	[0.735, 0.915]	4.7	[3.7, 6.6]
RFD_{0-50}	0.686	[0.509, 0.822]	16.3	[12.7, 23.2]
RFD_{0-100}	0.767	[0.621, 0.871]	16.7	[12.9, 23.8]
RFD_{0-150}	0.850	[0.746, 0.919]	11.6	[9.0, 16.4]
RFD_{0-200}	**0.907**	**[0.838, 0.951]**	**7.1**	**[5.6, 10.0]**
RFD_{0-250}	**0.939**	**[0.892, 0.968]**	**5.3**	**[4.2, 7.5]**

Notes: Bold font denotes good to excellent reliability. ICC = intraclass correlation, CI = confidence interval, CV = coefficient of variation, IFP = isometric first pull, IMTP = isometric mid-thigh pull, $Force_{50}$ = force at 50 ms, $Force_{100}$ = force at 100 ms, $Force_{150}$ = force at 150 ms, $Force_{200}$ = force at 200 ms, RFD_{0-50} = rate of force development from 0 to 50 ms, RFD_{0-100} = rate of force development from 0 to 100 ms, RFD_{0-150} = rate of force development from 0 to 150 ms, RFD_{0-200} = rate of force development from 0 to 200 ms, RFD_{0-250} = rate of force development from 0 to 250 ms.

Measures obtained from snatch, clean, IFP, and IMTP across 16 weeks are displayed in Table 2. No significant difference between weeks was observed from all measured variables (p = 0.151 – 0.975). At week 0, significant and near perfect correlations were observed between IFP and IMTP PF with snatch and clean PP and MP (r = 0.967 – 0.989, $p < 0.001$) (Table 3).

Significant and very large correlations were observed between IFP $Force_{200}$, IFP RFD_{0-200} and RFD_{0-250} with snatch and clean PP and MP (r = 0.753 – 0.852, p = 0.006 – 0.010) (Table 3). At week 8, significant and near perfect correlations were observed between IFP and IMTP PF with snatch and clean PP and MP (r = 0.966 – 0.991, $p < 0.001$) (Table 4). Significant and very large correlations were observed between IFP $Force_{50}$ and $Force_{200}$ with snatch and clean PP and MP (r = 0.777 – 0.840, p = 0.002 – 0.008) (Table 4). At week 16, significant and near perfect correlations were observed between IFP and IMTP PF with snatch and clean PP and MP (r = 0.954 – 0.977, $p < 0.001$) (Table 5). Significant and very large correlations were observed between IFP $Force_{50}$ and $Force_{200}$ with snatch and clean PP and MP (r = 0.803 – 0.865, p = 0.002 – 0.02) (Table 5). Fisher r-z transformation analysis showed no significant change in correlation magnitude between snatch and clean PP and MP with all isometric variables across 16 weeks (p = 0.053 – 0.497) (Supplementary Table 1 – 4).

Table 2: Snatch, clean and isometric test measures across 16 weeks expressed as mean (SD).

	Week 0 *M* (SD)	Week 8 *M* (SD)	Week 16 *M* (SD)	ANOVA *p*	Week 0 vs 8 *g* [95% CI]	Week 0 vs 16 *g* [95% CI]	Week 8 vs 16 *g* [95% CI]
Snatch							
PP (W)	1864.2 (679.5)	1926.0 (694.1)	1986.9 (720.4)	0.926	0.09 [-0.79, 0.96]	0.17 [-0.71, 1.05]	0.08 [-0.79, 0.96]
MP (W)	841.5 (295.1)	894.5 (339.4)	915.1 (357.4)	0.878	0.16 [-0.72, 1.04]	0.22 [-0.66, 1.09]	0.06 [-0.82, 0.93]
Clean							
PP (W)	1648.2 (523.7)	1723.0 (567.9)	1787.8 (606.4)	0.860	0.13 [-0.75, 1.01]	0.24 [-0.64, 1.12]	0.11 [-0.77, 0.98]
MP (W)	864.7 (298.5)	900.6 (322.2)	923.9 (343.4)	0.918	0.11 [-0.77, 0.99]	0.18 [-0.7, 1.05]	0.07 [-0.81, 0.94]
IFP							
PF (N)	1974.6 (499.1)	2066.0 (475.3)	2220.3 (508.5)	0.540	0.18 [-0.7, 1.06]	0.47 [-0.42, 1.36]	0.3 [-0.58, 1.18]
$Force_{50}$ (N)	818.0 (122.9)	788.5 (119.0)	786.0 (155.0)	0.838	-0.23 [-1.11, 0.65]	-0.22 [-1.1, 0.66]	-0.02 [-0.89, 0.86]
$Force_{100}$ (N)	1128 (197.6)	1127.0 (167.4)	1104.4 (215.1)	0.952	-0.01 [-0.88, 0.87]	-0.11 [-0.99, 0.77]	-0.11 [-0.99, 0.76]
$Force_{150}$ (N)	1367.3 (194.9)	1370.7 (347.4)	1551.6 (273.5)	0.975	0.01 [-0.86, 0.89]	0.74 [-0.16, 1.65]	0.55 [-0.34, 1.45]
$Force_{200}$ (N)	1551.6 (273.5)	1601.4 (317.7)	1610.5 (428.5)	0.920	0.16 [-0.72, 1.04]	0.16 [-0.72, 1.03]	0.02 [-0.85, 0.9]
$RFD_{0\text{-}50}$ ($N \cdot s^{-1}$)	1869.9 (960.7)	2108.6 (1009.3)	2023.5 (1159.3)	0.875	0.23 [-0.65, 1.11]	0.14 [-0.74, 1.02]	-0.07 [-0.95, 0.8]
$RFD_{0\text{-}100}$ ($N \cdot s^{-1}$)	4187.2 (1736.8)	4433.5 (1752.8)	4192.6 (1981.1)	0.943	0.14 [-0.74, 1.01]	0.00 [-0.87, 0.88]	-0.12 [-1, 0.75]
$RFD_{0\text{-}150}$ ($N \cdot s^{-1}$)	4229.1 (1107.7)	4628.3 (1389.9)	4397.8 (2072.0)	0.902	0.30 [-0.58, 1.19]	0.10 [-0.78, 0.97]	-0.13 [-1, 0.75]
$RFD_{0\text{-}200}$ ($N \cdot s^{-1}$)	4162.3 (1324.9)	4607.5 (1370.5)	4630.4 (1782.6)	0.738	0.32 [-0.57, 1.2]	0.29 [-0.6, 1.17]	0.01 [-0.86, 0.89]
$RFD_{0\text{-}250}$ ($N \cdot s^{-1}$)	3902.4 (1408.8)	4003.9 (1141.1)	4315.1 (1536.3)	0.784	0.08 [-0.8, 0.95]	0.27 [-0.61, 1.15]	0.22 [-0.66, 1.1]
IMTP							
PF (N)	2706.4 (626.2)	2831.8 (633.4)	3016.3 (629.2)	0.549	0.19 [-0.69, 1.07]	0.47 [-0.42, 1.36]	0.28 [-0.6, 1.16]
$Force_{50}$ (N)	832.9 (134.4)	869.1 (155.8)	891.3 (168.6)	0.695	0.24 [-0.64, 1.12]	0.37 [-0.52, 1.25]	0.13 [-0.75, 1.01]
$Force_{100}$ (N)	1214.4 (202.7)	1319.2 (338.2)	1440.7 (292.1)	0.221	0.36 [-0.52, 1.24]	0.86 [-0.05, 1.78]	0.37 [-0.52, 1.25]
$Force_{150}$ (N)	1593.5 (351.8)	1720.0 (434.3)	1882.5 (355.4)	0.256	0.31 [-0.58, 1.19]	0.78 [-0.13, 1.69]	0.39 [-0.49, 1.28]
$Force_{200}$ (N)	1914.2 (355.4)	2073.0 (539.7)	2190.8 (449.9)	0.429	0.33 [-0.55, 1.22]	0.65 [-0.25, 1.55]	0.23 [-0.65, 1.11]
$RFD_{0\text{-}50}$ ($N \cdot s^{-1}$)	2718.9 (1221.6)	3565.7 (1728.3)	4294.3 (2336.4)	0.173	0.54 [-0.35, 1.43]	0.81 [-0.1, 1.72]	0.34 [-0.54, 1.22]
$RFD_{0\text{-}100}$ $N \cdot s^{-1}$)	5176.6 (2067.7)	6226.3 (3083.0)	7676.6 (3084.7)	0.151	0.38 [-0.5, 1.27]	0.91 [-0.01, 1.83]	0.45 [-0.44, 1.34]
$RFD_{0\text{-}150}$ (N.s-^{1})	5975.5 (2318.4)	6833.5 (2613.3)	7989.1 (2372.5)	0.199	0.33 [-0.55, 1.22]	0.82 [-0.09, 1.73]	0.44 [-0.44, 1.33]
$RFD_{0\text{-}200}$ ($N \cdot s^{-1}$)	6043.9 (1972.4)	6878.0 (2371.4)	7542.0 (1963.5)	0.299	0.37 [-0.52, 1.25]	0.73 [-0.18, 1.63]	0.29 [-0.59, 1.17]
$RFD_{0\text{-}250}$ ($N \cdot s^{-1}$)	5652.5 (1618.8)	6358.6 (1841.6)	6519.6 (1703.3)	0.498	0.39 [-0.49, 1.27]	0.50 [-0.39, 1.39]	0.09 [-0.79, 0.96]

Notes: PP = peak power, MP = mean power, IFP = isometric first pull, PF = peak force, IMTP = isometric mid-thigh pull, $Force_{50}$ = force at 50 ms, $Force_{100}$ = force at 100 ms, $Force_{150}$ = force at 150 ms, $Force_{200}$ = force at 200 ms, $RFD_{0\text{-}50}$ = rate of force development from 0 to 50 ms, $RFD_{0\text{-}100}$ = rate of force development from 0 to 100 ms, $RFD_{0\text{-}150}$ = rate of force development from 0 to 150 ms, $RFD_{0\text{-}200}$ = rate of force development from 0 to 200 ms, $RFD_{0\text{-}250}$ = rate of force development from 0 to 250 ms.

Table 3: Correlation between snatch and clean power measures with isometric test measures at Week 0 expressed as *r* [95% CI].

	Snatch PP	Snatch MP	Clean PP	Clean MP
IFP				
PF	0.983 [0.929, 0.996]**	0.987 [0.945, 0.997]**	0.989 [0.953, 0.998]**	0.985 [0.938, 0.997)**
$Force_{50}$	0.293 [-0.413, 0.779]	0.254 [-0.447, 0.762]	0.301 [-0.405, 0.783]	0.318 [-0.390, 0.789]
$Force_{100}$	0.371 [-0.338, 0.811]	0.405 [-0.302, 0.824]	0.435 [-0.268, 0.836]	0.427 [-0.277, 0.833]
$Force_{150}$	0.611 [-0.030, 0.896]	0.618 [-0.019, 0.898]	0.654 [0.042, 0.909]*	0.651 [0.037, 0.908]*
$Force_{200}$	0.793 [0.327, 0.949]*	0.792 [0.325, 0.949]*	0.815 [0.381, 0.955]*	0.813 [0.377, 0.954]*
$RFD_{0\text{-}50}$	0.120 [-0.551, 0.967]	0.143 [-0.535, 0.709]	0.179 [-0.541, 0.727]	0.170 [-0.515, 0.722]
$RFD_{0\text{-}100}$	0.049 [-0.602, 0.656]	0.118 [-0.552, 0.696]	0.134 [-0.541, 0.704]	0.110 [-0.558, 0.692]
$RFD_{0\text{-}150}$	0.450 [-0.250, 0.841]	0.510 [-0.176, 0.863]	0.525 [-0.156, 0.868]	0.503 [-0.186, 0.860]
$RFD_{0\text{-}200}$	0.753 [0.234, 0.938]*	0.768 [0.267, 0.942]*	0.776 [0.286, 0.944]**	0.767 [0.266, 0.942]*
$RFD_{0\text{-}250}$	0.827 [0.412, 0.958]*	0.847 [0.466, 0.963]**	0.852 [0.480, 0.964]**	0.844 [0.458, 0.962]**
IMTP				
PF	0.969 [0.869, 0.993]**	0.971 [0.880, 0.993]**	0.970 [0.873, 0.993]**	0.967 [0.862, 0.992]**
$Force_{50}$	0.706 [0.137, 0.925]	0.738 [0.202, 0.934]	0.740 [0.207, 0.934]	0.731 [0.188, 0.932]
$Force_{100}$	0.276 [-0.428, 0.772]	0.378 [-0.330, 0.814]	0.340 [-0.368, 0.799]	0.306 [-0.40, 0.785]
$Force_{150}$	0.364 [-0.345, 0.808]	0.450 [-0.251, 0.841]	0.407 [-0.299, 0.825]	0.379 [-0.329, 0.814]
$Force_{200}$	0.545 [-0.129, 0.875]	0.614 [-0.025, 0.897]	0.585 [-0.071, 0.888]	0.563 [-0.103, 0.880]
$RFD_{0\text{-}50}$	0.139 [0.538, 0.707]	0.236 [-0.462, 0.754]	0.226 [-0.471, 0.749]	0.190 [-0.499, 0.732]
$RFD_{0\text{-}100}$	-0.147 [0.532, 0.711]	-0.040 [-0.653, 0.605]	-0.081 [-0.676, 0.578]	-0.119 [-0.696, 0.552]
$RFD_{0\text{-}150}$	0.120 [-0.551, 0.697]	0.212 [-0.482, 0.742]	0.166 [-0.518, 0.720]	0.135 [-0.541, 0.705]
$RFD_{0\text{-}200}$	0.358 [-0.350, 0.806]	0.431 [-0.273, 0.834]	0.399 [-0.307, 0.822]	0.375 [-0.334, 0.813]
$RFD_{0\text{-}250}$	0.626 [0.006, 0.901]	0.676 [0.082, 0.916]	0.654 [0.041, 0.909]	0.637 [0.012, 0.904]

Notes: $*p < 0.05$. $**p < 0.01$. IFP = isometric first pull, IMTP = isometric mid-thigh pull, PF = peak force, $Force_{50}$ = force at 50 ms, $Force_{100}$ = force at 100 ms, $Force_{150}$ = force at 150 ms, $Force_{200}$ = force at 200 ms, $RFD_{0\text{-}50}$ = rate of force development from 0 to 50 ms, $RFD_{0\text{-}100}$ = rate of force development from 0 to 100 ms, $RFD_{0\text{-}150}$ = rate of force development from 0 to 150 ms, $RFD_{0\text{-}200}$ = rate of force development from 0 to 200 ms, $RFD_{0\text{-}250}$ = rate of force development from 0 to 250 ms.

Table 4: Correlation between snatch and clean power measures with isometric test measures at Week 8 expressed as *r* (95%CI).

	Snatch PP	Snatch MP	Clean PP	Clean MP
IFP				
PF	0.982[0.924, 0.996]**	0.987 [0.944, 0.997]**	0.991 [0.960, 0.998]**	0.980 [0.914, 0.995]**
$Force_{50}$	0.777 [0.289, 0.945]*	0.780 [0.295, 0.945]*	0.777 [0.288, 0.944]*	0.795 [0.332, 0.949]*
$Force_{100}$	0.360 [-0.348, 0.807]	0.370 [-0.339, 0.811]	0.382 [-0.326, 0.815]	0.379 [-0.329, 0.814]
$Force_{150}$	0.641 [0.019, 0.905]	0.646 [0.028, 0.907]	0.649 [0.033, 0.908]	0.653 [0.039, 0.909]
$Force_{200}$	0.836 [0.436, 0.960]*	0.837 [0.439, 0.961]*	0.833 [0.429, 0.960]*	0.840 [0.446, 0.961]*
$RFD_{0\text{-}50}$	0.178 [-0.509, 0.726]	0.184 [-0.504, 0.729]	0.202 [-0.490, 0.738]	0.217 [-0.478, 0.745]
$RFD_{0\text{-}100}$	-0.129 [-0.702, 0.545]	-0.120 [-0.697, 0.551]	-0.101 [-0.687, 0.564]	-0.111 [-0.692, 0.557]
$RFD_{0\text{-}150}$	0.349 [-0.360, 0.802]	0.356 [-0.353, 0.805]	0.368 [-0.340, 0.810]	0.354 [0.354, 0.805]
$RFD_{0\text{-}200}$	0.664 [0.059, 0.912]*	0.667 [0.063, 0.912]*	0.666 [0.063, 0.913]*	0.665 [0.061, 0.912]*
$RFD_{0\text{-}250}$	0.739 [0.205, 0.934]*	0.741 [0.210, 0.935]*	0.744 [0.215, 0.935]*	0.740 [0.208, 0.934]*
IMTP				
PF	0.970 [0.875, 0.993]**	0.976 [0.898, 0.994]**	0.979 [0.909, 0.995]**	0.966 [0.858, 0.992]**
$Force_{50}$	0.638 [0.013, 0.904]	0.637 [0.013, 0.904]	0.633 [0.006, 0.903]	0.665 [0.061, 0.913]
$Force_{100}$	0.336 [-0.373, 0.797]	0.339 [-0.369, 0.798]	0.341 [-0.367, 0.799]	0.356 [-0.353, 0.805]
$Force_{150}$	0.417 [-0.289, 0.829]	0.420 [-0.285, 0.830]	0.424 [-0.281, 0.832]	0.422 [-0.282, 0.831]
$Force_{200}$	0.605 [-0.039, 0.894]	0.606 [-0.038, 0.894]	0.611 [-0.031, 0.896]	0.614 [-0.026, 0.897]
$RFD_{0\text{-}50}$	-0.096 [-0.684, 0.568]	-0.095 [-0.684, 0.568]	-0.094 [-0.683, 0.570]	-0.068 [-0.669, 0.587]
$RFD_{0\text{-}100}$	0.016 [-0.620, 0.639]	0.019 [-0.618, 0.641]	0.022 [-0.616, 0.643]	0.033 [-0.609, 0.649]
$RFD_{0\text{-}150}$	0.185 [-0.503, 0.730]	0.189 [-0.500, 0.731]	0.194 [-0.496, 0.734]	0.187 [-0.502, 0.731]
$RFD_{0\text{-}200}$	0.458 [-0.241, 0.844]	0.459 [-0.243, 0.844]	0.464 [-0.234, 0.846]	0.465 [-0.233, 0.847]
$RFD_{0\text{-}250}$	0.670 [0.07, 0.914]	0.669 [0.068, 0.914]	0.673 [0.076, 0.915]	0.678 [0.084, 0.916]

Notes: $*p < 0.05$. $**p < 0.01$. IFP = isometric first pull, IMTP = isometric mid-thigh pull, PF = peak force, $Force_{50}$ = force at 50 ms, $Force_{100}$ = force at 100 ms, $Force_{150}$ = force at 150 ms, $Force_{200}$ = force at 200 ms, $RFD_{0\text{-}50}$ = rate of force development from 0 to 50 ms, $RFD_{0\text{-}100}$ = rate of force development from 0 to 100 ms, $RFD_{0\text{-}150}$ = rate of force development from 0 to 150 ms, $RFD_{0\text{-}200}$ = rate of force development from 0 to 200 ms, $RFD_{0\text{-}250}$ = rate of force development from 0 to 250 ms.

Table 5: Correlation between snatch and clean power measures with isometric test measures at Week 16 expressed as *r* (95%CI).

	Snatch PP	Snatch MP	Clean PP	Clean MP
IFP				
PF	0.954 [0.811, 0.989]**	0.965 [0.854, 0.992]**	0.973 [0.887, 0.994]**	0.965 [0.853, 0.992]**
$Force_{50}$	0.803 [0.350, 0.952]*	0.811 [0.370, 0.954]*	0.825 [0.405, 0.957]*	0.844 [0.457, 0.962]*
$Force_{100}$	0.586 [-0.069, 0.888]	0.618 [-0.019, 0.898]	0.644 [0.024, 0.906]*	0.638 [0.013, 0.904]*
$Force_{150}$	0.563 [-0.103, 0.881]	0.587 [-0.067, 0.888]	0.613 [-0.026, 0.897]	0.628 [-0.003, 0.901]
$Force_{200}$	0.824 [0.403, 0.957] *	0.839 [0.444, 0.961]*	0.856 [0.490, 0.965]*	0.865 [0.517, 0.968]*
RFD_{0-50}	0.457 [-0.243, 0.844]	0.476 [-0.219, 0.851]	0.507 [-0.181, 0.861]	0.545 [-0.129, 0.874]
RFD_{0-100}	0.142 [-0.535, 0.709]	0.177 [-0.509, 0.726]	0.203 [-0.489, 0.738]	0.192 [-0.498, 0.733]
RFD_{0-150}	0.317 [-0.391, 0.789]	0.344 [-0.364, 0.800]	0.372 [-0.337, 0.811]	0.385 [-0.323, 0.817]
RFD_{0-200}	0.714 [0.154, 0.927]	0.733 [0.191, 0.932]	0.752 [0.231, 0.938]*	0.761 [0.251, 0.940]*
RFD_{0-250}	0.731 [0.188, 0.932]	0.750 [0.227, 0.937]	0.769 [0.270, 0.942]*	0.778 [0.291, 0.945]*
IMTP				
PF	0.967 [0.863, 0.992]**	0.974 [0.890, 0.994]**	0.977 [0.903, 0.995]**	0.963 [0.847, 0.991]**
$Force_{50}$	0.635 [0.008, 0.903]	0.635 [0.009, 0.904]	0.653 [0.040, 0.909]	0.691 [0.109, 0.920]
$Force_{100}$	0.276 [-0.428, 0.772]	0.271 [-0.432, 0.770]	0.291 [-0.414, 0.778]	0.331 [-0.378, 0.795]
$Force_{150}$	0.344 [-0.364, 0.800]	0.353 [-0.356, 0.804]	0.376 [-0.332, 0.813]	0.402 [-0.305, 0.823]
$Force_{200}$	0.580 [-0.079, 0.886]	0.592 [-0.060, 0.890]	0.612 [-0.028, 0.896]	0.633 [0.006, 0.903]
RFD_{0-50}	-0.256 [-0.763, 0.445]	-0.266 [-0.767, 0.437]	-0.246 [-0.758, 0.454]	-0.198 [-0.736, 0.493]
RFD_{0-100}	-0.180 [-0.727, 0.507]	-0.188 [-0.731, 0.501]	-0.171 [-0.723, 0.514]	-0.137 [-0.706, 0.539]
RFD_{0-150}	-0.048 [-0.658, 0.600]	-0.044 [-0.656, 0.602]	-0.024 [-0.644, 0.615]	0.048 [-0.629, 0.630]
RFD_{0-200}	0.309 [-0.398, 0.786]	0.318 [-0.389, 0.790]	0.340 [-0.369, 0.798]	0.362 [-0.346, 0.808]
RFD_{0-250}	0.561 [-0.106, 0.880]	0.572 [-0.090, 0.883]	0.591 [-0.062, 0.890]	0.608 [-0.035, 0.895]

Notes: $*p < 0.05$. $**p < 0.01$. IFP = isometric first pull, IMTP = isometric mid-thigh pull, PF = peak force, $Force_{50}$ = force at 50 ms, $Force_{100}$ = force at 100 ms, $Force_{150}$ = force at 150 ms, $Force_{200}$ = force at 200 ms, RFD_{0-50} = rate of force development from 0 to 50 ms, RFD_{0-100} = rate of force development from 0 to 100 ms, RFD_{0-150} = rate of force development from 0 to 150 ms, RFD_{0-200} = rate of force development from 0 to 200 ms, RFD_{0-250} = rate of force development from 0 to 250 ms.

4. Discussion

The purpose of the study was to determine the relationship between weightlifting performance with force-time characteristics obtained from IFP and IMTP over several mesocycles. The current results showed no significant difference in correlation magnitude of IFP and IMTP variables with PP or MP of the SN and CN. In addition, the correlation magnitude did not change significantly over a 16-week training period. Hence, our hypothesis was not supported. While it was not the primary purpose of the study to monitor the changes in both isometric strength measures and weightlifting performance across the 16-week, the current results showed that there was no significant change in both isometric and weightlifting measures. Hence, the results were not able to affirm the findings of James et al. (2023) who reported the disproportionate changes between isometric and dynamic strength measures.

Similar to the findings of Ben-Zeev et al. (2022) and Joffe et al. (2021), the current study showed significant correlation between PF obtained from IFP and IMTP with SN and CN performance ($r = 0.954 – 0.989$). However, while both previous studies reported greater correlation magnitude between weightlifting performance with IFP PF then with IMTP PF, the current results showed no difference. This contradiction was apparent throughout the 16 weeks. A possible reason could be the difference in the way weightlifting performance was measured. In both earlier studies, weightlifting performance was determined by the highest amount of weight lifted during SN and CN, while the current study determined performance by the lifting velocity of SN and CN at 85% season best. Despite the difference in performance measures, all three studies were in agreement that PF obtained from both IFP and IMTP may provide insights into weightlifting performance.

The RFD is one of the important determinants of weightlifting performance (Beckham et al., 2013; Haff et al., 2005). Apart from the current study, Ben-Zeev et al. (2022) was the only one that compared the correlation between RFD obtained from both IFP and IMTP with weightlifting performance. Similar to the results presented by Ben-Zeev et al. (2022), the current results showed significant correlations between IFP RFD_{0-200} and RFD_{0-250} with SN and CN performance during week 0 ($r = 0.753 – 0.852$), while IFP RFD at other time point and IMTP RFD showed no significant or meaningful correlation to SN and CN performance ($r = -0.040 – 0.740$). However, although the correlation magnitude of IFP RFD_{0-200} and RFD_{0-250} with SN and CN performance did not change significantly at week 8 ($r = 0.664 – 0.744$), they did not reach statistical significance after *p*-values were adjusted for familywise error rates. Furthermore, at week 16, IFP RFD_{0-200} and RFD_{0-250} were only significantly correlated to CN performance ($r = 0.752 – 0.778$). Nevertheless, the large to very large correlations between IFP RFD_{0-200} and RFD_{0-250} with SN and CN performance were observed across 16 weeks. These findings indicate that RFD within the 200 ms timeframe during the first pull of the weightlifting action may have greater importance on the success of SN and CN performance than RFD at later phases of the lifts.

Interestingly, while IFP RFD_{0-50} showed no significant correlation to both SN and CN performance, IFP $Force_{50}$ at week 8 and 16 showed significant and large correlations to all SN and CN measures (r = 0.777 – 0.844). One possible reason could be due to the poor reliability of the IFP RFD_{0-50} measure. Thus, resulting in low correlation to SN and CN. While this finding suggests that early force development may be a determinant of weightlifting performance, the IFP $Force_{50}$ obtained during week 0 showed insignificant and small correlation with SN and CN performance. The reason for this observation is unknown as the data for IFP $Force_{50}$ showed good reliability, and there was no major change in training program across the 16 weeks. Conversely, IFP $Force_{200}$ was observed to have a very large and significant correlation with SN and CN performance across the 16 weeks (r = 0.792 – 0.865). This was consistent with the observation on IFP RFD_{0-200} and RFD_{0-250}, thus, further indicating the importance of force development around the 200 ms timeframe on SN and CN performance. It has been observed that the duration of the first pull for both SN and CN is around the 400 ms timeframe (Gourgoulis et al., 2000; Sorenson et al., 2022). Considering the short distance travelled with this period, weightlifters would need to have generated sufficient amount of force to overcome the inertial to lift the weight off the ground within the 200 ms timeframe. Hence, the significant correlation observed between IFP $Force_{200}$, RFD_{0-200} and RFD_{0-250} with SN and CN performance observed.

Several limitations should be taken into consideration when interpreting the current results. Firstly, the weightlifting performance in this study was determined by the mean and peak power during SN and CN at 85% season's best instead of a 1RM. This differs from the previous two studies by Ben-zeev et al. (2022) and Joeffe et al. (2021). Hence, direct comparison of data may not be accurate. However, the use of power measurement at submaximal load provides relevance to the daily training environment, and such measure has been determined to be a good predictor of weightlifting performance (Garhammer, 1993). Secondly, the current sample size of participants did not allow for subgroup comparison, although the sample size was limited by using the national training squad. Hence, future studies may consider filling this gap in the current literature.

In conclusion, the results of this study show that peak force in the first and second pull positions exhibit a near perfect correlation with weightlifting performance. Furthermore, the current findings also showed the importance of early force development and RFD at 200 ms at the first pull position on weightlifting performance The results of this study also suggest that the force generation capabilities at both first and second pull positions should be equally addressed during training.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgment

The authors would like to thank all participants for their participation in the study.

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Appendix

Supplementary Table 1: Comparison of correlations to snatch peak power (*p*).

	Week 0 vs 8	Week 0 vs 16	Week 8 vs 16
IFP			
PF	0.478	0.172	0.186
$Force_{50}$	0.084	0.066	0.448
$Force_{100}$	0.491	0.299	0.291
$Force_{150}$	0.463	0.445	0.409
$Force_{200}$	0.405	0.433	0.471
$RFD_{0\text{-}50}$	0.456	0.243	0.279
$RFD_{0\text{-}100}$	0.372	0.427	0.305
$RFD_{0\text{-}150}$	0.411	0.385	0.473
$RFD_{0\text{-}200}$	0.368	0.437	0.429
$RFD_{0\text{-}250}$	0.333	0.322	0.487
IMTP			
PF	0.488	0.476	0.464
$Force_{50}$	0.408	0.404	0.496
$Force_{100}$	0.451	0.500	0.451
$Force_{150}$	0.453	0.483	0.437
$Force_{200}$	0.433	0.462	0.471
$RFD_{0\text{-}50}$	0.329	0.226	0.378
$RFD_{0\text{-}100}$	0.379	0.475	0.356
$RFD_{0\text{-}150}$	0.450	0.376	0.330
$RFD_{0\text{-}200}$	0.411	0.459	0.371
$RFD_{0\text{-}250}$	0.444	0.425	0.371

Notes: IFP = isometric first pull, IMTP = isometric mid-thigh pull, PF = peak force, $Force_{50}$ = force at 50 ms, $Force_{100}$ = force at 100 ms, $Force_{150}$ = force at 150 ms, $Force_{200}$ = force at 200 ms, $RFD_{0\text{-}50}$ = rate of force development from 0 to 50 ms, $RFD_{0\text{-}100}$ = rate of force development from 0 to 100 ms, $RFD_{0\text{-}150}$ = rate of force development from 0 to 150 ms, $RFD_{0\text{-}200}$ = rate of force development from 0 to 200 ms, $RFD_{0\text{-}250}$ = rate of force development from 0 to 250 ms.

Supplementary Table 2: Comparison of correlations to snatch mean power (*p*).

	Week 0 vs 8	Week 0 vs 16	Week 8 vs 16
IFP			
PF	0.500	0.174	0.174
$Force_{50}$	0.071	0.052	0.437
$Force_{100}$	0.469	0.292	0.266
$Force_{150}$	0.465	0.464	0.429
$Force_{200}$	0.403	0.398	0.495
$RFD_{0\text{-}50}$	0.469	0.242	0.267
$RFD_{0\text{-}100}$	0.327	0.455	0.288
$RFD_{0\text{-}150}$	0.361	0.351	0.490
$RFD_{0\text{-}200}$	0.346	0.440	0.403
$RFD_{0\text{-}250}$	0.292	0.305	0.485
IMTP			
PF	0.429	0.459	0.470
$Force_{50}$	0.359	0.357	0.497
$Force_{100}$	0.467	0.411	0.444
$Force_{150}$	0.491	0.414	0.441
$Force_{200}$	0.492	0.474	0.484
$RFD_{0\text{-}50}$	0.265	0.169	0.370
$RFD_{0\text{-}100}$	0.456	0.389	0.348
$RFD_{0\text{-}150}$	0.482	0.099	0.107
$RFD_{0\text{-}200}$	0.475	0.403	0.379
$RFD_{0\text{-}250}$	0.490	0.374	0.383

Notes: IFP = isometric first pull, IMTP = isometric mid-thigh pull, PF = peak force, Force50 = force at 50 ms, Force100 = force at 100 ms, Force150 = force at 150 ms, Force200 = force at 200 ms, RFD0-50 = rate of force development from 0 to 50 ms, RFD0-100 = rate of force development from 0 to 100 ms, RFD0-150 = rate of force development from 0 to 150 ms, RFD0-200 = rate of force development from 0 to 200 ms, RFD0-250 = rate of force development from 0 to 250 ms.

Supplementary Table 3: Comparison of correlations to clean peak power (*p*-value).

	Week 0 vs 8	Week 0 vs 16	Week 8 vs 16
IFP			
PF	0.425	0.198	0.150
$Force_{50}$	0.087	0.053	0.401
$Force_{100}$	0.453	0.288	0.249
$Force_{150}$	0.494	0.449	0.455
$Force_{200}$	0.458	0.399	0.440
$RFD_{0\text{-}50}$	0.482	0.240	0.254
$RFD_{0\text{-}100}$	0.329	0.447	0.283
$RFD_{0\text{-}150}$	0.356	0.359	0.497
$RFD_{0\text{-}200}$	0.332	0.457	0.372
$RFD_{0\text{-}250}$	0.301	0.323	0.456
IMTP			
PF	0.368	0.401	0.466
$Force_{50}$	0.351	0.375	0.435
$Force_{100}$	0.499	0.459	0.459
$Force_{150}$	0.485	0.473	0.457
$Force_{200}$	0.470	0.469	0.499
$RFD_{0\text{-}50}$	0.272	0.184	0.385
$RFD_{0\text{-}100}$	0.423	0.432	0.358
$RFD_{0\text{-}150}$	0.478	0.22	0.205
$RFD_{0\text{-}200}$	0.441	0.449	0.391
$RFD_{0\text{-}250}$	0.475	0.424	0.399

Notes: IFP = isometric first pull, IMTP = isometric mid-thigh pull, PF = peak force, Force50 = force at 50 ms, Force100 = force at 100 ms, Force150 = force at 150 ms, Force200 = force at 200 ms, RFD0-50 = rate of force development from 0 to 50 ms, RFD0-100 = rate of force development from 0 to 100 ms, RFD0-150 = rate of force development from 0 to 150 ms, RFD0-200 = rate of force development from 0 to 200 ms, RFD0-250 = rate of force development from 0 to 250 ms.

Supplementary Table 4: Comparison of correlations to clean mean power (*p*-value).

	Week 0 vs 8	Week 0 vs 16	Week 8 vs 16
IFP			
PF	0.393	0.219	0.298
$Force_{50}$	0.079	0.045	0.389
$Force_{100}$	0.457	0.287	0.253
$Force_{150}$	0.497	0.471	0.468
$Force_{200}$	0.437	0.367	0.432
$RFD_{0\text{-}50}$	0.464	0.205	0.232
$RFD_{0\text{-}100}$	0.339	0.438	0.284
$RFD_{0\text{-}150}$	0.366	0.391	0.473
$RFD_{0\text{-}200}$	0.348	0.489	0.358
$RFD_{0\text{-}250}$	0.297	0.358	0.433
IMTP			
PF	0.489	0.457	0.468
$Force_{50}$	0.405	0.440	0.464
$Force_{100}$	0.458	0.479	0.479
$Force_{150}$	0.462	0.480	0.482
$Force_{200}$	0.442	0.419	0.477
$RFD_{0\text{-}50}$	0.313	0.231	0.402
$RFD_{0\text{-}100}$	0.388	0.486	0.375
$RFD_{0\text{-}150}$	0.460	0.435	0.396
$RFD_{0\text{-}200}$	0.419	0.489	0.408
$RFD_{0\text{-}250}$	0.446	0.465	0.411

Notes: IFP = isometric first pull, IMTP = isometric mid-thigh pull, PF = peak force, Force50 = force at 50 ms, Force100 = force at 100 ms, Force150 = force at 150 ms, Force200 = force at 200 ms, RFD0-50 = rate of force development from 0 to 50 ms, RFD0-100 = rate of force development from 0 to 100 ms, RFD0-150 = rate of force development from 0 to 150 ms, RFD0-200 = rate of force development from 0 to 200 ms, RFD0-250 = rate of force development from 0 to 250 ms.