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ORIGINAL ARTICLE

Divergent muscle functional and architectural responses to two successive high intensity resistance exercise sessions in competitive weightlifters and resistance trained adults

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Abstract Peak force (PF), contractile rate of force development (RFD) and contractile impulse (CI) are of great importance to competitive weightlifters (WL). These athletes routinely perform successive bouts of high-intensity resistance exercise (HIRE) within the same day (double-day training) with the aim of improving muscular function and weightlifting performance. The purpose of this investigation was to determine and compare the PF, contractile RFD and CI responses to double-day training between WL and resistance trained (RT) adults ($n = 16$ per group). Furthermore, we sought to establish whether acute changes in muscle function were associated with acute changes in muscle architecture. Isometric front squat PF, contractile RFD, CI and the pennation angle (θ_p), anatomical and physiological thickness of the m. vastus lateralis (VL) were determined before and after two equivalent HIRE sessions separated by 4–6 h rest. Each session consisted of ten single repetitions of the dynamic barbell front squat interspersed with 2-min rest, using a load equivalent to 90% of the pre-session PF. Weightlifters demonstrated greater PF at all time points when compared to RT adults and exhibited no significant within or between session changes in PF, contractile RFD or CI. Conversely, RT adults demonstrated within- and between-session decreases in PF and between-session increases in contractile RFD and CI. As no correlations were found between the relative within-session changes in muscle function and the concomitant changes in muscle architecture, other factors must contribute to the divergent responses in PF, contractile RFD and CI between WL and RT adults.

Keywords Isometric · Peak force · Rate of force development · Contractile impulse · Pennation angle · Muscle thickness

Abbreviations

WL	Weightlifters
RT	Resistance trained
PF	Peak force
RFD	Rate of force development
CI	Contractile impulse
HIRE	High-intensity resistance exercise
VL	m. vastus lateralis
θ_p	Pennation angle
PCSA	Physiological cross-sectional area
MVC	Maximal voluntary contraction

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Introduction

Competitive weightlifting is a strength and power sport in which two, multi-joint, whole body movement lifts are performed in competition; the snatch and the clean and jerk. During the performance of these lifts, weightlifters (WL) have demonstrated some of the highest absolute and relative maximal power outputs reported in the literature

(Garhammer 1980, 1991). Maximal voluntary isometric peak force (PF) is strongly related to weightlifting performance and other dynamic muscle actions (Haff et al. 2005; Hakkinen et al. 1986; Stone et al. 2003, 2005). However, while PF is reached in the vicinity of 300–600 ms (Aagaard et al. 2002; Thorstensson et al. 1976; Zatsiorsky 2003), WL achieve maximum barbell velocities and peak power outputs in <260 ms (Campos et al. 2006; Garhammer 1991; Gourgoulis et al. 2000, 2009). Thus, the contractile rate of force development (RFD), defined as the slope of the force–time curve (Aagaard et al. 2002), is of great importance to WL (Haff et al. 2005). Furthermore, the contractile impulse (CI), defined as the integral of the force–time curve (Aagaard et al. 2002), is another measure of muscular function relevant to weightlifting performance. Contractile impulse factors in the overall influence of the various time-related contractile RFD parameters (Aagaard et al. 2002; Baker et al. 1994). As mass remains constant during the performance of a weightlifting movement, an increase in CI would be associated with a higher movement velocity, a decrease in movement time and a greater displacement of the loaded barbell (Garhammer and Gregor 1992; Schilling et al. 2008). To enhance muscular function and competitive performance, the training practices of WL often include successive high-intensity resistance exercise (HIRE) sessions that are performed within the same day. The muscle functional responses of WL to each session may explain how these athletes are able to sustain high loads during successive training sessions.

To improve muscular strength and power, the American College of Sports Medicine recommends performing 4–6 sessions.per week of moderate [30–60% of 1 repetition max (1RM)] to high intensity (≥80% 1RM) resistance exercise. However, it is common for strength and power athletes to divide a given training volume across two sessions that are performed on the same day. Such "double-day" protocols produce significantly greater increases in muscular strength, hypertrophy and maximal neural activation of the trained musculature when compared to performing the same training volume across one daily session (Häkkinen and Kallinen 1994; Hartman et al. 2007). It is known that PF declines in resistance-trained (RT) adults when resistance exercise is performed twice during the same day (Chiu et al. 2004). Conversely, the RFD does not appear to be compromised in well-trained adults following two successive resistance exercise sessions of differing intensity and modality (Chiu et al. 2004; Häkkinen 1992, 1988). To the best of our knowledge, no investigation has examined the acute CI responses to double-day training. Consistent with these findings, double-day programs are often split according to muscle group (e.g. upper vs. lower body) and training intensity (e.g. high vs. low) to enable recovery between subsequent sessions (Häkkinen and Kallinen 1994; Kraemer et al. 1998). However, WL are known to perform two or more HIRE sessions per day, inclusive of exercises for the same major muscle groups, 6 or 7 days per week (Garhammer and Takano 2003; Stone et al. 2006; Zatsiorsky 1995). As certain kinematic parameters (e.g. maximum barbell acceleration, velocity and displacement) must be achieved in order to successfully perform weightlifting movements (Garhammer 1985, 1991, 1993), we anticipate that PF, contractile RFD and CI are maintained (or enhanced) in WL during successive HIRE bouts. It has been proposed that the maintenance (or enhancement) of muscular function within and between bouts of HIRE may be attributable to acute changes in the architecture of skeletal muscle (Mahlfeld et al. 2004; Tillin and Bishop 2009).

Peak force, contractile RFD and CI are influenced by a number of morphological factors including muscle fiber type, tendon properties, pennation angle (θ_p) and muscle thickness (Blazevich et al. 2007; Cormie et al. 2011; Kawakami et al. 1995). Pennation angle (θ_p), defined as the angle of the muscle fascicles relative to the points of insertion at the tendon or aponeurosis determines the arrangement of sarcomeres within a muscle (Aagaard et al. 2001; Narici 1999). A large anatomical θ_p allows more sarcomeres to be arranged in parallel. This in turn increases muscle thickness and PCSA (i.e. the cross-sectional area perpendicular to the line of fascicles) which are both positively associated with PF (Blazevich et al. 2007; Cormie et al. 2011; Narici 1999). In addition, muscle fibers of a greater θ_p operate closer to their optimum length which is advantageous to force production (Blazevich 2006). Conversely, smaller anatomical θ_p allow more sarcomeres to be arranged in series which facilitates a rapid transmission of force to the tendon, thus increasing contractile RFD and CI (Fukunaga et al. 1997; Gans and Gaunt 1991; Kawakami et al. 1993; Kumagai et al. 2000).

Acute changes in θ_p occur in response to the recent history of previous muscular contractions. These changes appear to be influenced by the total exercise volume. High-power dynamic resistance exercise performed to failure and a high volume of isometric maximal voluntary contractions (MVC) have been shown to acutely increase θ_p by 10–11%, respectively (Csapo et al. 2011; Kubo et al. 2001). In contrast, an acute decrease in θ_p of ~11% has been reported 3–6 min following three isometric MVC (Mahlfeld et al. 2004). Theoretically, an increased post-contraction θ_p, and consequently an increased PCSA, would increase PF. Conversely, a post-contraction reduction in θ_p may provide a mechanical advantage for rapid force transmission to the tendon, thereby improving contractile RFD and CI. However, no investigation to date has determined the functional significance of such changes in skeletal muscle architecture.

The first objective of this investigation was to determine and compare the PF, contractile RFD and CI before and after each of two equivalent HIRE sessions performed within the same day between WL and RT adults. The second objective was to establish whether acute changes in PF, contractile RFD and CI were associated with acute changes in θ_p or thickness of the m. vastus lateralis (VL). It was hypothesized that: (1) PF, contractile RFD and CI would decrease within and between the two HIRE sessions in the RT adults only and (2) the maintenance and/or enhancement of PF in WL would be associated with an acute relative increase in VL θ_p and subsequently muscle thickness.

Methods

Subjects

Sixteen competitive WL and sixteen RT adults volunteered to participate (Table 1). As a requirement of the study, all participants were free from acute or chronic injury at the time of data collection and were not using any performance enhancing supplements (e.g. creatine) or banned substances (as per the 2010 World Anti-Doping Code). Data was obtained from the WL during a normal training phase (i.e. not during a competition peaking phase) during which they performed 8.0 ± 0.8 training sessions per week. Nine WL were New Zealand National record holders at the time of data collection. Resistance trained adults were required to have performed regular resistance exercise (i.e. more than once per week for the previous year), and were able to perform a free-weight barbell front squat to a parallel depth (defined as the top of the thighs being parallel to the ground) with a weight equivalent to or greater than their body mass. All participants provided written informed consent prior to commencing. The investigation was approved by the University of Auckland Human Participants Ethics Committee.

Table 1 Physical characteristics of weightlifters (WL) and resistance trained adults (RT)

Group	Age	Mass (kg)	Height (m)
WL			
All ($N = 16$)	21.5 ± 1.0	81.54 ± 6.3	1.68 ± 0.02
Men ($N = 13$)	20.7 ± 1.0	85.54 ± 7.3	1.71 ± 0.02
Women ($N = 3$)	25.0 ± 3.2	64.67 ± 5.7	1.56 ± 0.03
RT			
All ($N = 16$)	26.2 ± 0.8**	75.51 ± 2.9	1.75 ± 0.02*
Men ($N = 13$)	26.5 ± 0.9**	79.13 ± 2.6	1.78 ± 0.02*
Women ($N = 3$)	24.7 ± 1.8	59.80 ± 3.2	1.65 ± 0.05

Data are presented as mean (±SE)

* Significant difference between groups ($P < 0.05$)

** Significant difference between groups ($P < 0.001$)

Experimental design

Each participant was instructed to arrive at the facility in the morning in a rested and fed state. After obtaining initial (pre-session) ultrasound images of the VL, participants performed a standardized warm up, followed by three isometric MVC in the front squat position during which muscle function was measured. Participants were then required to complete a HIRE session consisting of a dynamic warm-up and ten high intensity dynamic front squats with 2 min rest between repetitions. Post-session ultrasound images were obtained directly after the tenth front squat and the muscle function testing was repeated. The complete sequence was repeated 4–6 h later.

Muscle architecture

A 7.5 MHz linear array transducer (Chison 8300 Digital Ultrasound System, China) was used to obtain sagittal plane ultrasound images of the VL. This widely used imaging technique is sensitive to small changes in skeletal muscle architecture (Loram et al. 2006) and has proven suitable for the non-invasive quantification of healthy and diseased pennate muscle (Pillen et al. 2007; Walker et al. 2004). Participants lay supine with their right leg supported by a custom-built A-frame structure which positioned the knee at an angle of 45°. This position has been shown to reduce fascicle curvature and improve the reliability of repeated measurements, whilst enabling the detection of inter-individual differences in muscle architecture (Blazevich et al. 2007). The probe was applied mid-thigh such that images were recorded at 50% of femur length. Water-soluble transmission gel was used between the probe and skin surface to aid in acoustic contact. Minimal consistent pressure of the probe was applied to avoid compression of the muscle. Muscle thickness and θ_p were determined from the images using digitizing software (Scion Image for Windows, Scion Corporation, MD, USA). Pennation angle was defined as the angle between the echos of the interfaces between the muscle fiber bundles and the deep aponeurosis (Aagaard et al. 2001). Anatomical muscle thickness was determined as the mean of duplicate measurements of the perpendicular distance between the superficial and deep aponeuroses (Fig. 1). Physiological muscle thickness was calculated as the square root of [anatomical muscle thickness^2 + (tan θ_p × anatomical muscle thickness)^2] (Blazevich et al. 2007).

Muscle function

All force–time curve analyses were conducted using a calibrated 59.5 × 89.5 cm force plate (Kelba Onspot Power Plate, Sydney, Australia) placed within a custom-set up power rack with safety bars (Fig. 2).

Participants performed a warm up of ten dynamic front squats to a parallel depth using a standard 20 kg barbell, followed by ten repetitions with 50% of their recently attained one repetition maximum. Participants were then required to assume a stationary front squat to parallel depth (with a standard barbell) on the force plate to 'zero' the system. A second set of safety bars were inserted into the power rack at a height that enabled participants to perform an isometric front squat at a parallel thigh position (Fig. 3).

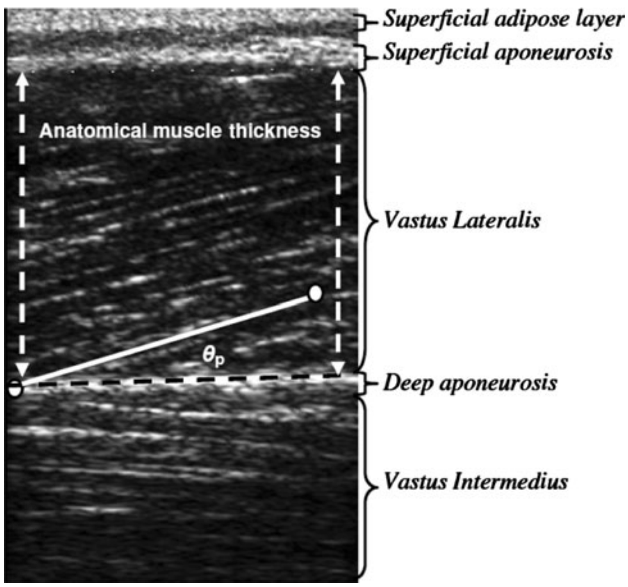
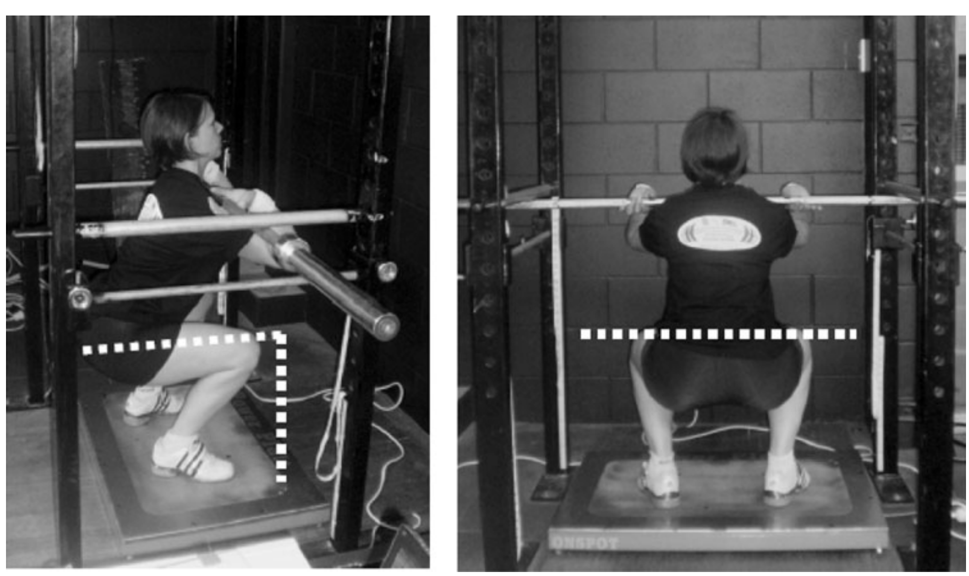


Fig. 1 Sagittal plane ultrasound image of the vastus lateralis recorded at 50% femur length with the knee positioned at 45°. Anatomical muscle thickness was measured as the perpendicular distance between the superficial and deep aponeuroses. Muscle fiber pennation angle (θ_p) was measured as the angle between the VL muscle fascicles and the deep aponeurosis

Participants were instructed to raise the barbell so it 'lightly' touched the upper safety bars, and upon the count of three, performed an isometric contraction at ~50% of their maximum perceived effort for three seconds. This familiarization step was repeated at ~80% of the participant's maximum perceived effort. Following the familiarization, the participants completed three isometric MVC. Participants were instructed to push as hard and as fast as possible and each attempt was separated by a 1 min rest period.

All data was sampled at 1,000 Hz (Chart™ V5.5.5, AD Instruments) with a low-pass digital filter applied with a cut-off frequency set at 15 Hz. The procedure generated a force–time curve from which PF, contractile RFD, peak RFD and CI were calculated. Contractile RFD, peak RFD and CI were determined from the trial exhibiting the highest PF. Contractile RFD was calculated as the average slope of the force–time (Δforce/Δtime) curve over time intervals 0–30, 0–50, 0–100, 0–200 and 0–400 ms relative to the onset of contraction. Contractile impulse was derived as the area under the force–time curve across the same time intervals. The peak RFD was determined as the peak slope of the force–time (Δforce/Δtime) curve relative to the onset of contraction. The onset of contraction was defined as the time point on the force–time curve where force exceeded the baseline by >7.5 N (Aagaard et al. 2002). Where a negative deflection indicative of a counter-movement was observed, the trial was excluded from analysis. The PF, contractile RFD and CI were expressed relative to body mass. Contractile RFD is strongly influenced by the PF capacity of a muscle (Andersen and Aagaard 2006; Blazevich et al. 2009). Therefore, to assess the potential influence of other physiological factors on rapid force

Fig. 2 Peak force and contractile rate of force development were calculated from the vertical force component of the participant's ground reaction force during an isometric maximal voluntary contraction in a front squat position



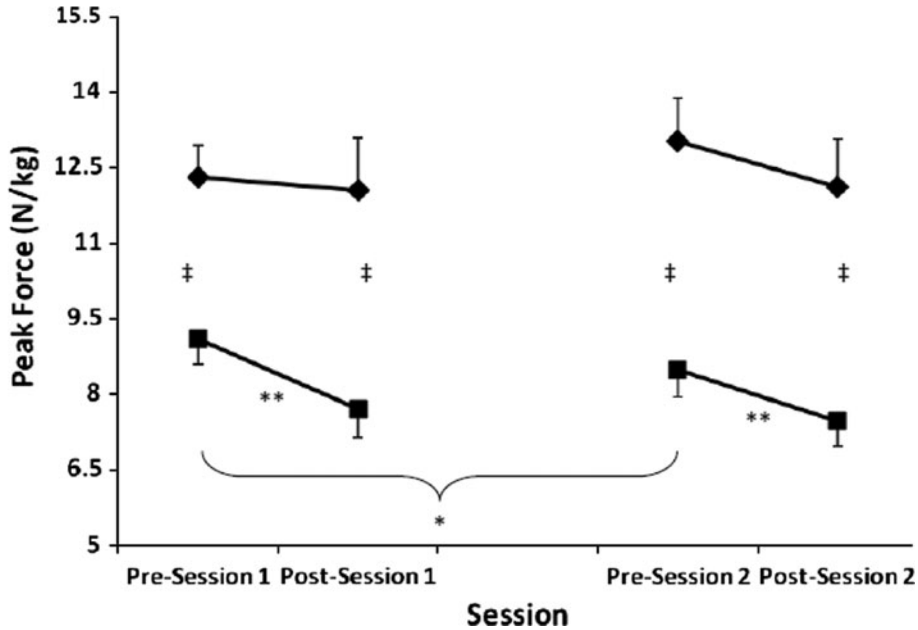


Fig. 3 Mean (SE) pre- and post-session peak force relative to body mass (N kg^{-1}) in weightlifters (*closed diamond*) and resistance trained adults (*closed square*) for two high intensity resistance exercise sessions performed on the same day. *Significant difference between sessions for group ($P < 0.05$); **Significant difference within session for group ($P < 0.01$); ‡Significant difference between groups at the same time point ($P < 0.001$)

generation (without the influence of PF), contractile RFD was also expressed relative to PF [relRFD = (RFD/PF) × 100] (Blazevich et al. 2009). The test–retest reliability (intra-class correlation co-efficient) for PF and contractile RFD, determined from the three pre-session 1 maximal trials, were 0.92 and 0.50–0.83, respectively.

Peak force, contractile RFD and CI are routinely determined using isometric contractions (Blazevich et al. 2008; Chiu et al. 2004; Häkkinen et al. 1992, 1988). The effectiveness of isometric measurements to assess dynamically induced training adaptations can be enhanced by selecting a body position specific to the dynamic performance of interest (Haff et al. 1997; Stone et al. 2003; Wilson and Murphy 1996). The isometric front squat was chosen due to its similarity with the clean phase of the competitive clean and jerk and other complementary exercises that are used by WL and RT adults (i.e. dynamic front squat and power clean). Furthermore, as maximal muscle activation is enhanced during isometric bilateral versus unilateral contractions (Behm et al. 2003), we were confident that this testing procedure would provide a valid representation of the PF, contractile RFD and CI responses following the dynamic bilateral exercise sessions (Aagaard et al. 2002; Baker et al. 1994).

Exercise sessions

Each exercise session was comprised of 10 dynamic parallel front squats (with 2-min rest between each repetition) with a load equivalent to 90% of the participant's pre-session PF. Before starting each exercise session, participants performed three warm-up front squats sets (3 repetitions at 65%, 2 repetitions at 75% and 1 repetition at 85% of the equivalent pre-session PF) with the depth of each repetition confirmed visually by an investigator. The warm-up protocol was of a low volume to minimize any fatigue prior to the exercise session. The two exercise sessions were separated by 4–6 h rest in accordance with previous investigations (Chiu et al. 2004; Häkkinen 1992, 1988).

Statistical analyses

Data are presented as mean ± SE. Independent samples *t* tests were used to assess differences between the descriptive characteristics of WL and RT adults. Where data did not follow a normal distribution according to Shapiro–Wilk testing, analyses were performed on log-transformed data. Two factor group (WL, RT) by time (pre-session 1, post-session1, pre-session 2, post-session 2) repeated-measures analysis of variance (ANOVA) was used to investigate each variable (PF, contractile RFD, relRFD, CI, θ_p and muscle thickness). The analyses tested for main effects of group and time and any interaction between group and time. Where a significant main effect was found by ANOVA, post hoc paired comparisons were made using the method of Student–Newman–Keuls. Effect sizes were calculated according to the method of Cohen where $d = 0.8$ is considered a large effect, $d = 0.5$ is moderate, and $d = 0.2$ a small effect size (Cohen 1992). To test for an association between skeletal muscle function and architecture, Pearson product moment correlations were used to evaluate: (1) pre-session PF and VL θ_p and, (2) the relative within-session changes in PF, contractile RFD, relRFD and CI and the relative within-session changes in VL θ_p and muscle thickness. Statistical significance was set at $P < 0.05$. Data were analyzed with SigmaPlot 11.0 statistical software (Chicago, IL, USA).

Results

The mean body mass did not differ between the groups, whereas the WL were younger ($P < 0.001$; $d = 1.1$) and shorter than RT adults ($P < 0.05$; $d = 0.77$) (Table 1). All participants were able to complete the exercise sessions as per the prescribed protocol, thereby enabling all repetitions within a session to be performed at the same relative load (90% of pre-session PF).

Peak force

Main effects of group ($P < 0.001$), time ($P < 0.001$) and an interaction between group and time existed for PF ($P < 0.01$) (Fig. 3). Post hoc paired comparisons showed that the PF in WL was higher when compared to RT adults at all time points ($P < 0.001$; $d = 1.11$–1.24) (Fig. 4). In addition, WL demonstrated no significant within- (session 1: $P = 0.49$; $d = 0.07$; session 2: $P = 0.08$; $d = 0.25$) or between-session ($P = 0.22$; $d = 0.24$) differences in PF. Conversely, PF in the RT adults decreased by 16.0 ± 3.0% within session 1 ($P < 0.001$; $d = 0.64$) and by 12.2 ± 2.8% within session 2 ($P = 0.002$; $d = 0.47$). Furthermore, PF in RT adults pre-session 2 was 7.0 ± 2.6% lower than in pre-session 1 ($P < 0.05$; $d = 0.28$).

Contractile rate of force development

Contractile RFD was greater in WL than in RT adults at 0–100, 0–200 and 0–400 ms ($P < 0.05$). There were also main effects of time at 0–30 ms ($P < 0.05$) and an interaction between group and time at 0–200 ms ($P < 0.05$)

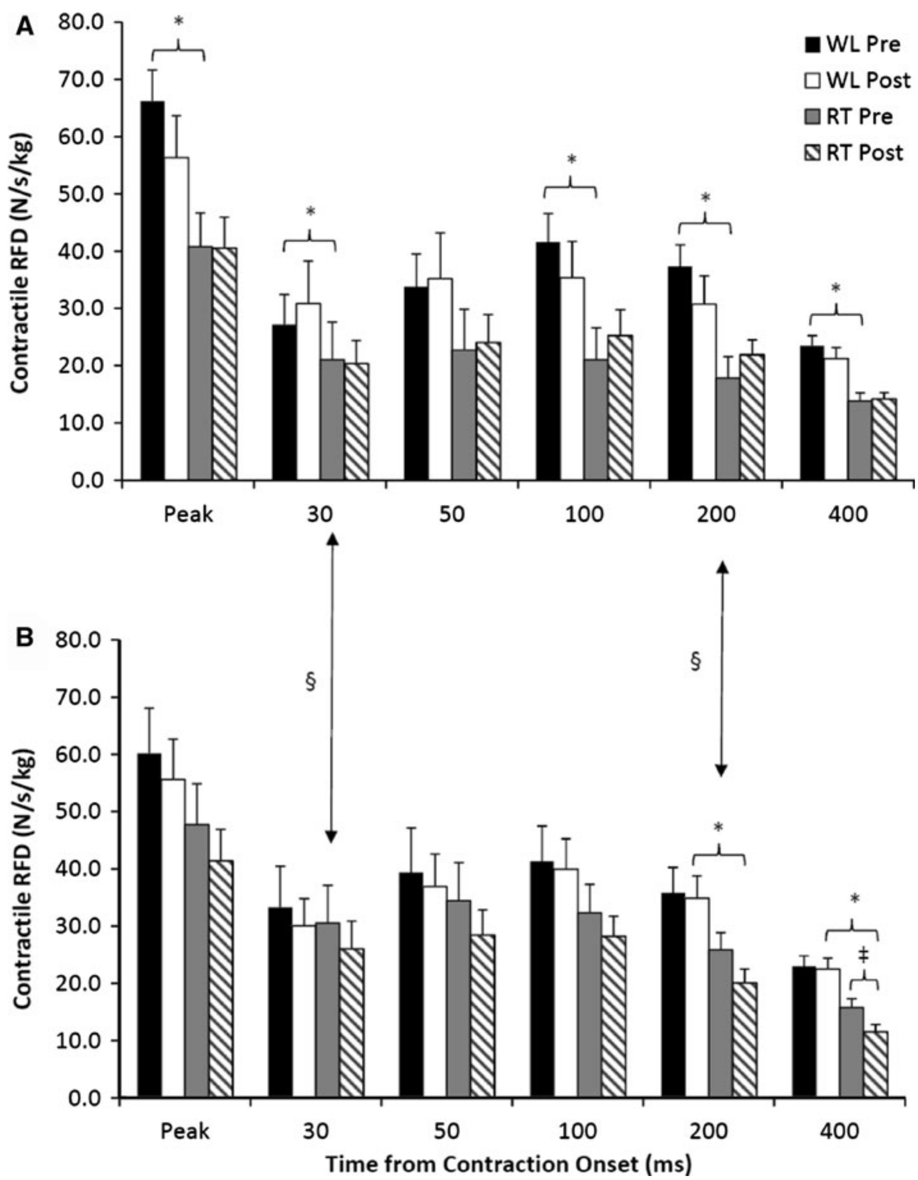


Fig. 4 Mean (SE) pre- and post-session contractile RFD relative to body mass (N s kg^{-1}) for session 1 (**a**) and session 2 (**b**). Contractile RFD was calculated at time intervals 0–30, 50, 100, 200, and 400 ms from the onset of contraction. The peak RFD was determined from within the entire contraction period. *Significant difference within session between groups ($P < 0.05$); ‡Significant difference within session for group ($P < 0.05$); §Significant difference between sessions at the same time from contraction onset for group ($P < 0.05$)

(Fig. 5). Post hoc comparisons showed that pre-session 1 contractile RFD was 22.6–52.3% higher in WL when compared to RT adults at 0–30 ($P = < 0.05$; $d = 0.26$), 0–100 ($P = < 0.05$; $d = 0.88$), 0–200 ($P = < 0.001$; $d = 1.09$) and 0–400 ms ($P = < 0.05$; $d = 1.19$). No significant within- or between-session differences in contractile RFD were observed for WL. Conversely, contractile RFD from 0–400 ms in the RT adults decreased by 22 ± 6.8% within session 2 ($P < 0.05$; $d = 0.7$). In addition, contractile RFD in the RT adults pre-session 2 was higher than the respective pre-session 1 values at 0–30 ($P < 0.05$; $d = 0.34$) and 0–200 ms ($P < 0.05$; $d = 0.57$). For relRFD, main effects of time were observed at 0–30 ms ($P < 0.05$) and group × time interactions were evident at 0–100, 0–200 and 0–400 ms ($P < 0.05$). Post hoc paired comparisons showed that the relRFD pre-session 1 was 33.3 ± 13.1, 25.6 ± 15.7 and 15.8 ± 7.8% higher in WL when compared to RT adults at 0–100 ms ($P = < 0.05$; $d = 0.60$), 0–200 ms ($P = < 0.001$; $d = 0.86$) and 0–400 ms ($P = < 0.05$; $d = 0.85$), respectively. No significant within- or between-session differences in relRFD were observed for WL. Conversely, RT adults demonstrated significant within- (pre-post session 1) ($P = < 0.05$; $d = 0.20$–0.85) and between-session (pre-session 1–pre-session 2) ($P = < 0.05$; $d = 0.49$–0.87) increases in relRFD at 0–30, 0–100, 0–200 and 0–400 ms.

Contractile impulse

Contractile impulse was greater in WL than in RT adults at 0–400 ms ($P < 0.05$). A group × time interaction was also evident at 0–400 ms ($P < 0.05$) (Fig. 5). Post hoc paired comparisons showed that pre-session 1 contractile impulse was 45.6 ± 6.8% higher in WL when compared to RT adults at 0–400 ms ($P = < 0.001$; $d = 0.97$). No significant within- or between-session differences in CI were

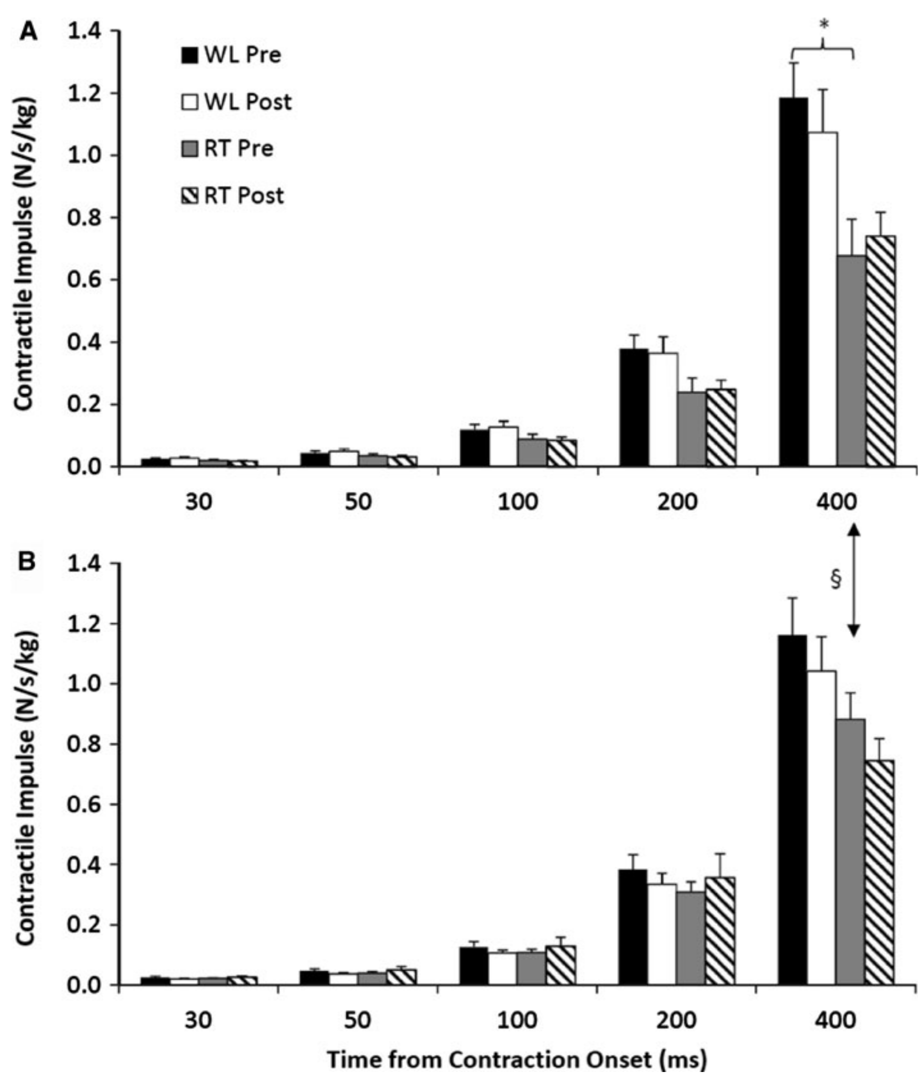


Fig. 5 Mean (SE) pre- and post-session contractile impulse relative to body mass (N s kg^{-1}) for session 1 (**a**) and session 2 (**b**). Contractile impulse was determined as the area under the force–time curve at time intervals 0–30, 50, 100, 200, and 400 ms from the onset of contraction. *Significant difference within session between groups ($P < 0.05$); §Significant difference between sessions at the same time from contraction onset for group ($P < 0.05$)

observed for WL. Conversely, CI in the RT adults pre-session 2 was higher than the respective pre-session 1 value at 0–400 ms ($P < 0.05$; $d = 0.49$).

Muscle architecture

The VL θ_p of the WL was greater than that of the RT adults ($P = < 0.05$) (Fig. 6), whereas no significant difference in anatomical ($P = 0.59$) or physiological ($P = 0.47$) muscle thickness existed between the groups (Table 2). The pre- and post-session 2 θ_p were 19.5% ($P < 0.05$; $d = 0.85$) and 22.5% ($P < 0.05$; $d = 0.88$) greater, respectively, in WL compared to the corresponding values in RT adults. No differences in VL θ_p existed between the groups within-session 1 (pre-session: $P = 0.20$; $d = 0.58$, post-session: $P = 0.09$; $d = 0.50$) (Fig. 6). Contrary to our expectations, there was no effect of time on θ_p ($P = 0.58$) or muscle thickness ($P = 0.11$).

No associations existed between pre-session PF and VL θ_p in WL (session 1: $r = 0.08$, $P = 0.76$; session 2: $r = -0.01$, $P = 0.97$) or RT adults (session 1: $r = -0.13$, $P = 0.64$, session 2: $r = -0.16$, $P = 0.57$). In addition, the relative within-session changes in PF, contractile RFD, relRFD and CI were not significantly correlated with the corresponding relative changes in θ_p or muscle thickness for either group.

Discussion

The major findings of this study were: (1) WL demonstrated a greater ability to generate and sustain PF during repeated HIRE bouts of the same muscle group; (2) WL demonstrated a greater ability to rapidly generate force in the later stages of muscle contraction (i.e. ≥100 ms) regardless of their PF, (3) despite exhibiting within-session and between-session decreases in PF, contractile RFD, relRFD and CI were maintained and/or enhanced between-sessions in RT adults, and, (4) the relative changes, or lack thereof, in PF, contractile RFD, relRFD and CI for WL and RT adults were not associated with relative changes in VL θ_p or muscle thickness for either group.

To the best of our knowledge, this is the first study to demonstrate divergent muscle functional and architectural responses of competitive WL and RT adults to two equivalent HIRE sessions performed on the same day. Our findings of sustained and/or enhanced contractile RFD, and CI between successive HIRE sessions extends previous

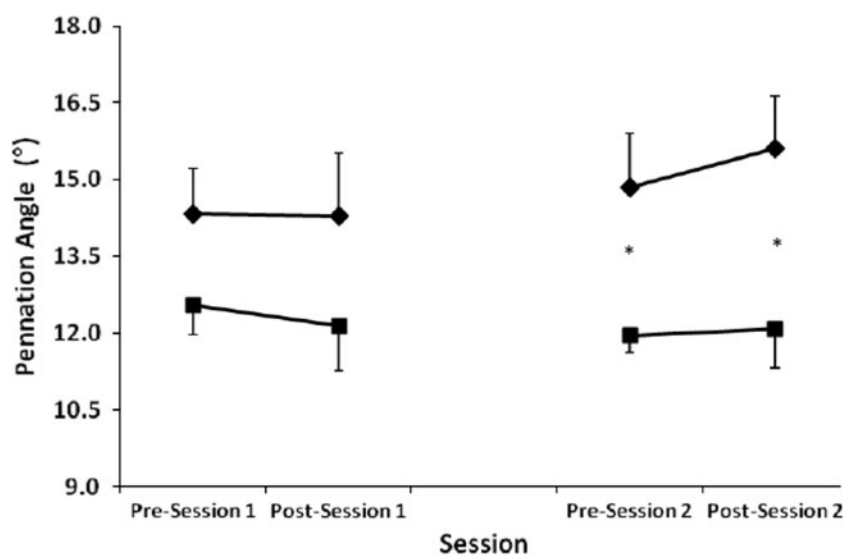


Fig. 6 Mean (SE) pre- and post-session vastus lateralis pennation angles in weightlifters (*closed diamond*) and resistance trained adults (*closed square*) across two high intensity resistance exercise sessions performed on the same day. *Significant difference between groups at the same time point ($P < 0.05$)

Table 2 Mean (±SE) muscle thickness of the vastus lateralis obtained from sagittal plane ultrasound images in weightlifters (WL) and resistance trained adults (RT) across two high intensity resistance exercise sessions performed on the same day

Variable	Group	Session 1		Session 2	
		Pre	Post	Pre	Post
Anatomical muscle thickness (mm)	WL	22.5 ± 0.9	23.0 ± 0.9	23.3 ± 1.0	23.5 ± 1.0
	RT	22.9 ± 0.8	22.9 ± 0.8	22.2 ± 0.9	22.7 ± 0.7
Physiological muscle thickness (mm)	WL	23.3 ± 0.9	23.7 ± 0.9	24.3 ± 1.1	24.6 ± 1.0
	RT	23.5 ± 0.8	23.5 ± 0.8	22.8 ± 0.9	23.3 ± 0.7

observations that such training does not compromise the ability to rapidly generate force in competitive WL and RT adults (Chiu et al. 2004; Häkkinen 1992, 1988).

Of particular interest in this study was the lack of association between PF, contractile RFD, relRFD, CI and skeletal muscle architecture. The VL θ_p of the RT group were consistent with values (similarly obtained with the knee at 45°) reported in recreationally active adults who took part in a five-week resistance exercise program (Blazevich et al. 2007**).** However, despite PF being 26–38% greater in WL when compared to RT adults, no significant association existed between pre-session PF and the larger θ_p exhibited by these athletes. Furthermore, the lack of change in VL θ_p over time is in contrast to previous evidence which suggests that the contraction history of a muscle can influence the post-contraction θ_p (Csapo et al. 2011; Kubo et al. 2001; Mahlfeld et al. 2004). However, the different exercise modes, intensities, volumes and muscle contraction types used in each investigation may partly account for this discrepancy. Following exhaustive dynamic and repeated isometric contractions, acute increases in θ_p and muscle thickness have been attributed to increased tendon compliance and muscle perfusion (Brancaccio et al. 2008; Csapo et al. 2011; Kubo et al. 2001). However, the high volume of repeated repetitions used in these investigations contrasts the relatively low volume, intermittent nature of our exercise protocol.

In addition to influencing skeletal muscle architecture, the compliance of tendon and elastic filaments also affects PF and contractile RFD (Bojsen-Møller et al. 2005). In response to active stretch, skeletal muscle stiffness increases via a Ca^{2+} dependent potentiation of elastic filaments (Bagni et al. 2004; Cormie et al. 2011; Joumaa et al. 2008; Rassier and Herzog 2002). Although a stiffer series elastic component promotes smaller changes in θ_p (Pearson and Onambele 2005), it has been associated with enhanced force generation (Joumaa et al. 2008; Rassier and Herzog 2002). Furthermore, previous research has shown that the stiffness of the tendon-aponeurosis complex may account for ~30% of the variance in contractile RFD (Bojsen-Møller et al. 2005). Therefore, it is possible that such a mechanism enabled WL and RT adults to sustain contractile RFD and CI despite exhibiting no significant within or between session changes in muscle architecture. In addition to the influence of mechanical stimuli, increases in tendon compliance and θ_p have been shown to occur in the evening, relative to the morning (Pearson and Onambele 2005). However, in the current investigation there is little evidence of such diurnal variation as no significant within- or between-session changes in VL θ_p occurred for either group. As no associations existed between the relative changes in muscle function and the relative changes, or lack thereof, in muscle architecture, other physiological factors must be responsible for the divergent responses in PF, contractile RFD and CI between WL and RT adults.

Contractile RFD during the early phase of muscle contraction (0–50 ms) is related to the intrinsic contractile properties of skeletal muscle (Aagaard et al. 2002). Conversely, maximal strength has been shown to account for approximately 80% of the variance in contractile RFD during the later stages (i.e. 100–250 ms) of muscle contraction in sedentary adults (Andersen and Aagaard 2006). In the current investigation, PF was not the underlying mechanism responsible for the divergent contractile RFD responses between groups pre-session 1 as relRFD (at $\geq$100 ms) remained significantly higher in WL when compared to RT adults. However, the significant within- and between-session increases in relRFD in the RT adults occurred as a function of their decreased ability to sustain PF and their ability to maintain and/or increase contractile RFD.

Temporal changes in contractile RFD and CI have been attributed to alterations in motor unit recruitment, firing frequency and synchronization (Aagaard et al. 2002; Mellor and Hodges 2005; Semmler 2002; Thorlund et al. 2008). Motor unit synchronization is a proposed training-induced adaptation of the nervous system that enables the co-activation of numerous muscle groups to effectively enhance force generation (Aagaard et al. 2002; Mellor and Hodges 2005; Semmler 2002). As contractile RFD and CI are paramount to weightlifting performance (Garhammer and Gregor 1992; Schilling et al. 2008), it is likely that training-induced improvements in inter-muscular coordination allow WL to maintain or enhance these variables during repeated dynamic exercise sessions. Although both experimental groups were familiar with the dynamic barbell front squat, we cannot discount the possibility that the WL demonstrated a more effective recruitment of agonist and synergistic muscle groups, and a decreased co- contraction of antagonists, during the performance of the dynamic exercise sessions (Cormie et al. 2011; Mellor and Hodges 2005; Milner-Brown and Lee 1975). However, since muscular function was assessed using an isometric test (relevant to the dynamic exercise of interest), the influence of potential differences in inter-muscular co-ordination between groups is likely to have been minimized.

Finally, as isometric PF is known to increase over the time course of a day (Gauthier et al. 1996; Martin et al. 1999; Tamm et al. 2009), such diurnal variation may partly account for the ability of WL to sustain PF. However, this time of day effect may have also masked the full extent of the RT group's decline in PF over the two HIRE sessions. Our inability to account for the influence of diurnal variation on muscle function and tendon compliance is therefore a limitation of our study.

Conclusion

As hypothesized, competitive WL demonstrated a greater ability to sustain PF across repeated HIRE bouts of the same muscle group when compared to RT adults. However, both highly-trained WL and RT adults sustained or increased their contractile RFD and CI in response to such training. Finally, the maintenance or enhancement of muscular function was not associated with acute changes in muscle architecture for either group. These findings have important practical implications for the prescription of HIRE programs intended to improve muscular strength and power. For example, due to the inability of RT adults to maintain PF across two successive HIRE, these individuals may benefit more from performing a single session of high-intensity strength training within a given day. However, due to their ability to maintain or improve contractile RFD and CI, it would be possible to perform a subsequent low- to moderate-intensity plyometric/speed training session within the same day. Further research in this area may enable a more precise application of training loads and intensities based upon an individual's muscle functional responses across multiple daily sessions.

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