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Large inter-individual variability in force-velocity profile changes in response to acute high-load resistance training

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ABSTRACT

Background: While the acute effects of high-load resistance training on the force generating capacity of muscles have been widely examined, limited data exist on the relationship with the force-velocity profile (FV). Evidence suggests high sensitivity of the vertical FV profile to monitor changes in the muscle's mechanical properties according to the type of the exercise protocol. However, the interpretation of the findings seems not as straightforward. Therefore, the purpose of this study was to examine the effects of a high-load resistance training protocol on the muscle's mechanical properties during loaded jumps and on the vertical force-velocity profile (FV) in relation to maximal strength. *Methods:* 29 resistance-trained male (mean age±SD: 35.4 ± 7.8 years) and 29 female athletes (mean age±SD: 32.5 ± 7.0 years) participated in the study. Five-repetition maximum (5RM) in back squat, unloaded countermovement jump (CMJ) and FV profile were assessed. Loaded jumps were performed against 25, 50, 75, and 100 percent of body mass. Participants performed exercise protocols corresponding to their 5RM. Immediately after, unloaded CMJ and FV profile measurements were repeated. *Results:* A significant decrease in CMJ height (~5–6%) and in average power (~4%) was recorded for both men and women. The FV profile did not change after the exercise protocol; however, there was a significant decrease in theoretical maximal power (from 4 to 5%) and in theoretical maximal velocity (~3%). Maximal strength was not associated with the changes in FV profile. *Conclusions:* Findings suggest that an acute high-load exercise decreased vertical jump performance and maximal power output, but without a concomitant change in FV profile. The large interindividual variability in FV measures indicates a less straightforward connection of the applied exercise with the acute response in the FV profile, highlighting the complexity of the FV profile to monitor changes in response to an acute training load.

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KEYWORDS

countermovement jump, vertical jump, back squat, training protocol

INTRODUCTION

Vertical jumping has been commonly used to monitor neuromuscular readiness [1] or acute neuromuscular fatigue [2, 3] with evidence demonstrating that acute resistance training decreases muscle force generating capacity and vertical jump performance [2]. This decline in performance has been related to metabolic and biochemical changes that may directly impair the contractile properties of muscles [4, 5]. The main metabolic by-products within the exercising muscle are inorganic phosphates (P_i) and hydrogen ions (H^+) [5]. Accumulation of these metabolites after high-intensity exercise may alter the actomyosin crossbridge activity and decrease myofibrillar calcium (Ca^{2+}) sensitivity [6]. As a result, impairments in force generation capacity and in muscle contraction velocity may be observed [5]. For instance, evidence suggests that the combined effects of an increase in P_i and H^+ concentration may lead to reductions of 36% in maximal force, 15% in maximal velocity, and 63% in peak power [5].

Force, velocity, and power are the main mechanical characteristics of single ballistic movements. Assessment of these variables and of their relationship has been used as a diagnostic tool to optimize strength and power training by establishing an individual's Force-velocity (FV) profile [7] under high-load and low-shortening velocity or low-load and high-shortening velocity conditions. According to previous reports, the FV profile can discriminate between athletes from sports of distinct strength training qualities [8–10] or it may reflect strength training adaptations according to the individual FV profile [11]. Yet, limited data are available on the acute changes of the FV profile after an exercise protocol. Data on how the force-velocity-power relationship changes under fatigued conditions can enhance our understanding about the muscle's mechanical properties providing valuable information in strength training according to the type and the intensity of specific exercise protocols.

It has been suggested that changes in the FV profile in response to an acute resistance exercise depend on the intensity and/or on the total number of repetitions of the exercise protocol [12]. High external loads predominantly affect the theoretical maximal force (F_0), whereas high training volume influences the theoretical maximal velocity (v_0) of the FV curve [12]. Changes in either variable (force or velocity) or in both will in turn alter maximal power (P_{max}) offering an overall evaluation of the muscles' neuromuscular state. We are familiar with one recent study, which examined changes in the vertical FV profile in response to resistance exercise [13]. The authors demonstrated that an acute high-load fatigue protocol significantly decreased F_0, whereas a low-load ballistic protocol decreased v_0, yet both protocols resulted in a comparable decrement in P_{max} [13]. These results suggest high sensitivity of the FV profile to monitor changes in the muscle's mechanical properties according to the applied fatigue protocol. Nevertheless, the interpretation of these findings is not sufficiently clear due to the remarkable heterogeneity in individual responses. For example, in the study of Li et al. [13], besides the small sample size, the results yielded notable interindividual variability, with almost half of the participants having minimal (or not any) differences in their response to the two fatigue protocols (high-load vs. low-load). In addition, the authors used each of the fatiguing set immediately before each load of the FV profile assessments. Such a design, however, does not reflect everyday training conditions, where accumulative fatigue and the rest periods between sets continuously compensate each other. From a practical perspective, we consider it important to examine training regimes that are often used in everyday practice. Assessments of FV profile in response to common resistance exercise can guide strength and power training in a more specific and individual manner.

An important aspect in acute fatigue-induced exercise studies is the total exercise volume expressed as total tonnage load. It is assumed that higher loads applied during exercise result in larger decrements in force-generating capacity. This may provide a possible explanation for the differences in fatiguability between men and women. Despite working at the same relative intensity, larger absolute strength for men is accompanied with larger absolute loads during exercise, which may potentially result in distinct changes in their FV profile. With regard to gender differences, most studies suggest less fatigability for women than for men [4, 14], attributed to neuromuscular, physiological, and anatomical differences [15]. Differences in muscle architecture and muscle proportion area supported by sex-specific hormones result in larger and more powerful force production for men compared with women and in less fatigability for the latter. In contrary to the general belief, however, Dinyer et al. [16] and Keller et al. [17] reported similar changes in force and neuromuscular performance for both men and women, suggesting that the different responses to fatigue between men and women are mode- and intensity-specific [16]. For instance, in low-intensity muscle contractions women seem to show better muscle perfusion than men resulting in higher resistance to fatigue [4]. Another relevant difference is the better vasodilator response women experience during exercise [18] having lower accumulation of metabolites, which, as mentioned earlier, have a crucial role in decreasing force-generating capacity and muscle performance.

To better understand how the vertical FV profile changes in response to acute resistance exercise and considering the limited data in this topic, the purpose of this study was (1) to examine the effects of a high-load training protocol on vertical jump mechanics and on the vertical FV profile, and (2) to test the hypothesis that larger tonnage loading during the acute exercise protocol is associated with larger fatiguability and accordingly with larger decrease in maximal force in resistance-trained men and women. For both men and women, it was hypothesized that the exercise would predominantly affect maximal force capacity, moving the FV profile towards larger force deficit. Further, we expected that women would demonstrate less fatiguability compared to men due to their lower absolute external loads used during exercise.

MATERIALS AND METHODS

Study design

We measured the force-velocity profile before and after an exercise protocol. Measurements were completed in two days. On the first day, five-repetition maximum (5RM) measurements were performed. On the second day, testing procedure started with a warmup, then the participants performed FV profile measurements, executed the exercise protocol using back squat exercise and subsequently went through the FV profile measurements again. Participants were asked to refrain from strenuous exercise 72 h prior to the measurements. The study was approved by the University's Research Ethics Committee (approval number: TE-KEB/NO34/2019).

Participants

A total of 58 resistance-trained male ($N = 29$) and female athletes ($N = 29$) volunteered to participate in the study. Participants were athletes from Olympic weightlifting and CrossFit competing at different levels (beginner to international level) with a minimum of one year experience in strength training and practicing at least three times a week for the last one year. None of the subjects reported illness or injury at the time of the measurements. All participants were informed about the type and the risks of the measurements and gave their written consent to participate in this study. Basic and maximal strength characteristics of the participants are presented in Table 1. We grouped men and women participants separately according to training status using as strength criteria their performance in back squat exercise. Two groups were formed (highly and moderately trained). The cut-off value in maximal back-squat was defined based on a recent study demonstrating that a well-balanced force – velocity profile was paired with performance in back-squat around 1.2 × bodyweight [19].

Five-repetition maximum measurement

Upon arrival, participants went through basic anthropometric measurements. Body height was measured with a stadiometer to the nearest 0.1 cm (DKSH Switzerland Ltd, Zurich, Switzerland). Body mass (BM) was measured with a digital scale (Seca 888) to the nearest 0.1 kg.

The procedure to determine the 5RM in back squat was the following: participants performed maximum five sets of five repetitions with two minutes of rest in-between with increasing weights to achieve the maximal load they can accomplish the squats with, using good technique. The steps to the 5RM back squat were the same for all participants. After squatting with empty bar, five repetitions were performed at 50-70-80-85 percent of their previously measured or perceived 1RM. 5RM was defined as the last load at which participants could perform five repetitions. All participants used high-bar back squats. Technique requirements included the hips to descend lower than the knees with straight back; when participants could not fulfill these requirements, the previous stage was accepted as his/her 5RM. According to the percentile tables of the National Strength and Conditioning Association (NSCA), 5RM can be performed at near 85% of the 1RM [20]. From the 5RM results the one-repetition maximum (1RM) was estimated using the Lombardi formula [21]: $1\text{RM} = 5\text{RM (kg)} \times 5^{0,10}$.

Force-velocity measurements

Vertical jump test was assessed on a force platform (FP4, HUR Labs Oy, Tampere, Finland) with a sampling rate of 1,000 Hz. First, subjects performed a unified warm-up protocol which contained mobilization exercises and running. Next, they performed five submaximal countermovement jumps (CMJ) to ensure proper technique. Participants performed three unloaded jumps and two loaded jumps against external loads corresponding to their 25th, 50th, 75th, and 100th percent of their body mass. During unloaded jumps hands were kept on the hips, whereas during loaded jumps on the bar. Loaded jumps were performed with free weights. Participants stepped under the barbell supported in a squat rack, then using the high-bar technique they placed the barbell on their back, moved out from the squat rack and stepped on the force platform. With the barbell on their back, they stood still on the force platform to measure total weight (body and external resistance) and then they executed the countermovement jump. Rest time between jumps was two minutes. Jumps with the highest jump height were used in the statistical analysis.

FV profile was calculated from the force and velocity data during the unloaded and loaded countermovement jumps. Average ground reaction force (GRF) for each loading condition was extracted from the force platform. We used the push-off phase from the moment ground reaction force exceeds body weight to the instant of takeoff. Net force was calculated by extracting the participants' body weight from total ground reaction force. Impulse during the unloaded jump was calculated as the product of net force (GRF – body weight) multiplied by the ground contact phase (from the moment GRF exceeds body weight to the moment it drops to become equal to body weight). Mean velocity for each loading condition was calculated from jump height as proposed previously [7]. We used the impulse-momentum methods to calculate the height of the vertical jump [22]. Using least squared linear regression we extrapolated the average force normalized to body weight and the average velocity to obtain the theoretical maximum force (F_0) and the theoretical maximum velocity (v_0). Theoretical maximum power ($P_{\max}$) was calculated as: $(F_0 \times v_0)/4$ [23]. FV imbalance ($\mathrm{FV}_{\mathrm{imb}}$) refers to the difference (in %) between the measured and the theoretical FV slopes [24]. The imbalance shows the direction and the magnitude of the FV profile and can be used to optimize strength and power training. For a given power to maximize performance in vertical jumping the following classification of the $\mathrm{FV}_{\mathrm{imb}}$ has been suggested in the literature: well-balanced (0 ± 10%), low deficit (10–40%), and high deficit (>40%) [11].

Exercise protocol

The exercise protocol included a back squat exercise using external loads corresponding to the five-repetition maximum (5RM) intensity. This exercise protocol is quite common in weightlifting and is designed to develop the athletes' maximal strength. Since in weightlifting the primary aim is to develop power and not maximal strength, during training athletes mostly use loads that develop strength but can be moved fast enough, similar to the demands of the weightlifting moves: snatch or clean and jerk. The 5RM load in back squat is close to most weightlifters' 1RM in front squat, which is a strong indicator for their clean and jerk performance. The participants performed 5 sets of 3 repetitions at their 5RM load with 2 min rest in-between. Total training volume corresponded with the upper limit according to a common method used in strength training as it was described by Prilepin [25].

Statistical analysis

Values are expressed as means ± *SD*. Normality was assessed using Shapiro-Wilk test. Basic and strength characteristics between men and women were analyzed using independent samples *t*-test (Hedges *g* effect size) A repeated measures ANOVA was used to examine differences between before and after the exercise protocol (within subjects effects), between male and female and between highly and moderately trained athletes (between subjects effects), and for their interaction. Effect sizes were evaluated using partial η^2 according to [26]: small (<0.02), moderate (≥0.06), and large (≥0.14). A priori sample size calculation (G^*Power 3.1.9.7) assuming 0.25 effect size f, type I error of 0.05, and 0.8 power suggested a required sample size of 34 participants for the repeated measures ANOVA. SPSS 29.0 (TIBCO software Inc, Palo Alto, CA, USA) package was used for the statistical analysis.

RESULTS

Normality test revealed normal distribution for the examined force-velocity variables for both male and female athletes separately. Mean (±*SD*) values for the vertical jump and the kinetic and kinematic variables before the exercise protocol are presented in Table 2. After the exercise, significant decrease of large effect size was found for jump height, impulse, and average power, whereas average force did not change. The magnitude of the changes for men and women was comparable, there was no interaction between sex and changes between pre and post exercise.

The results for the FV profile before and after the exercise protocol appear in Table 3. Both male and female participants had a significant decrease of large effect size in maximal power (P_{max}) and a significant decrease of medium effect size for v_0. F_0 did not change after the exercise protocol. Again, there was no interaction between sex and the effects of the exercise protocol. The ratio of the optimal to the measured slope (S_{fv}_act/S_{fv}_opt) represents the individual FV profile. Values below one refer to strength deficit, while values above one to velocity deficit. On average, FV profile was close to optimal for both men and women and did not change significantly after the exercise. The average FV imbalance (FVimb) was around 4% with a small, non-significant decrease after the exercise protocol.

Table 1. Basic and maximal strength characteristics of the participants

	Men (mean ± SD)	Women (mean ± SD)	Hedges' *g*
age (years)	35.4 ± 7.8	32.5 ± 7.0	0.39
body height (cm)	180.4 ± 6.8	166.2 ± 6.5*	2.15
body mass (kg)	87.5 ± 11.2	64.2 ± 8.4*	2.34
5RM (kg)	95.5 ± 22.7	68.6 ± 12.6*	1.46
1RM (kg)	112.2 ± 26.6	80.6 ± 14.8*	1.46
1RM/BW	1.29 ± 0.30	1.28 ± 0.29	0.86

1RM: One-repetition maximum; 5RM: five-repetition maximum; RM/BW: one-repetition maximum related to body mass. * = $P < 0.01$ compared to men.

Table 2. Results of the vertical jump derived variables before and after the exercise protocol for men and women (mean ± SD)

Variables		Pre exercise	Post exercise	Difference (%)	Repeated measures ANOVA
CMJ (cm)	Men	36.2 ± 4.8	34.3 ± 5.0	−5.5 ± 3.9	*F* (1, 54) = 103.8; *P* < 0.001
	Women	30.4 ± 4.7	28.6 ± 4.7	−6.0 ± 4.6	partial $\eta^2 = 0.66$
GRFavg (N)	Men	1152 ± 139	1147 ± 135	−0.3 ± 3.3	*F* (1, 54) = 0.6; *P* = 0.43
	Women	840 ± 105	838 ± 102	−0.1 ± 3.7	partial $\eta^2 = 0.01$
Pavg (W)	Men	1133 ± 141	1080 ± 158	−4.6 ± 8.0	*F* (1, 54) = 17.7; *P* < 0.001
	Women	786 ± 138	748 ± 129	−4.2 ± 9.6	partial $\eta^2 = 0.25$
Impulse (Ns)	Men	232.3 ± 29.8	225.4 ± 30.9	−3.0 ± 1.9	*F* (1, 54) = 130.1; *P* = <0.001
	Women	155.8 ± 18.2	150.8 ± 17.6	−3.2 ± 2.4	partial $\eta^2 = 0.71$

CMJ = Countermovement jump height; GRFavg = average ground reaction force; Pavg = average power.

Table 3. Results of the force-velocity profile before and after the exercise for men and women (mean±*SD*)

Variables		Pre exercise	Post exercise	Difference (%)	Repeated measures ANOVA
F_0 ($N\ kg^{-1}$)	Men	34.1 ± 3.4	33.5 ± 3.2	−1.2 ± 9.7	F (1, 54) = 1.07; P = 0.304
	Women	35.0 ± 5.4	34.6 ± 4.2	−0.3 ± 10.6	partial η^2 = 0.02
v_0 ($m{\cdot}s^{-1}$)	Men	2.9 ± 0.5	2.8 ± 0.5	−3.4 ± 12.8	F (1, 54) = 5.31; P = 0.025
	Women	2.5 ± 0.4	2.4 ± 0.4	−3.1 ± 15.1	partial η^2 = 0.09
P_{max} ($w\ kg^{-1}$)	Men	24.4 ± 3.6	22.9 ± 2.9	−5.6 ± 6.1	F (1, 54) = 35.73; $P < 0.001$
	Women	21.7 ± 3.3	20.7 ± 3.3	−4.8 ± 6.9	partial η^2 = 0.39
S_{fv}_act/	Men	0.9 ± 0.3	0.9 ± 0.2	3.8 ± 26.0	F (1, 54) = 0.54; P = 0.46
S_{fv}_opt	Women	1.0 ± 0.3	1.0 ± 0.2	3.9 ± 28.0	partial η^2 = 0.01
FV_{imb} (%)	Men	−10.9 ± 25.8	−11.1 ± 21.3	−23 ± 23.9	F (1, 54) = 2.35; P = 0.131
	Women	2.9 ± 27.3	1.2 ± 21.8	1.7 ± 28.3	partial η^2 = 0.04

F_0: theoretical maximum force; v_0: theoretical maximum velocity; P_{max}: theoretical maximum power; S_{fv}_act: slope of measured force-velocity relationship; S_{fv}_opt: slope of optimal force-velocity relationship; FV_{imb}: force-velocity imbalance; * = $P < 0.05$ compared to pre exercise.

Figure 1 shows changes (expressed in %) in average force and velocity after the exercise protocol for each unloaded and loaded condition. Changes in force production were larger for men compared to women, particularly in jumps against lower resistance. The magnitude of this

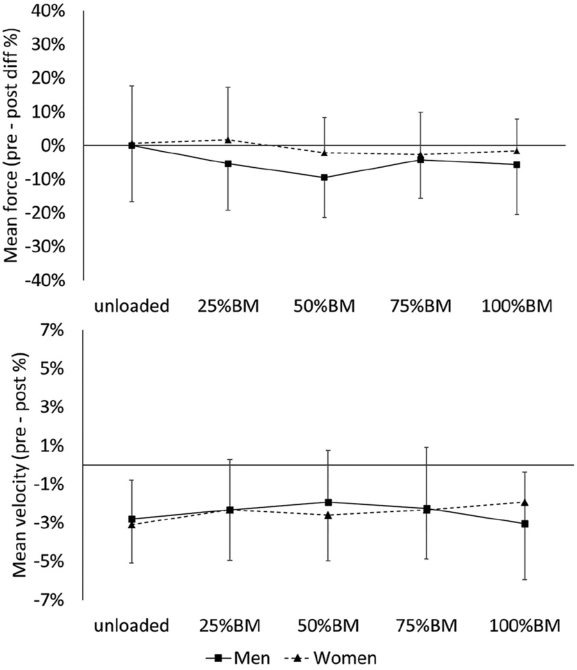

Fig. 1. Changes (in %) in mean force (upper panel) and mean velocity (lower panel) during unloaded and loading jumps after the exercise protocol. 25%BM = 25% external load of Body Mass; 50%BM = 50% external load of Body Mass; 75%BM = 75% external load of Body Mass; 100%BM = 100% external load of Body Mass

decrease between men and women was significant at the loaded jump against 50% of body mass (men: −1.89 ± 2.27% vs. women: −0.42 ± 1.78%; $t\ (54) = 2.68$; $P < 0.05$; $g = 0.72$). Changes in mean velocity showed a comparable pattern in both men and women exhibiting decreases of similar magnitude for all jumps which ranged on average from 2% to 3% after the exercise protocol.

Figure 2 shows the differences (in %) in the FV profile measures between pre and post exercise. Besides $P_{\max}$, changes in F_0, v_0, and FV profile showed large inter-individual variability. Changes from −20% to 27% and from −27% to 28% for F_0 and v_0, respectively, were noticed from pre- to post exercise, with about equal distribution of the participants with lower and higher values post exercise and with a similar pattern for both men and women. Changes in $P_{\max}$ were more consistent; most of the participants exhibited lower values post-exercise compared to pre-exercise (Fig. 2).

Table 4 summarizes the results of the changes in FV profile according to strength expertise groups. Highly (HT) and moderately trained (MT) subgroups were defined based on the 1RM in backsquat/body mass ratio using as cut off value the 1.2 backsquat/body mass according to a recent study demonstrating a positive connection of this value with a well-balanced FV profile (19). 17 male athletes were allocated to the highly trained and 11 to the moderately trained group with the performance in 1RM back squat/body mass being significant (HT = 1.49 ± 0.16 vs. MT = 0.98 ± 0.14; $P < 0.001$). Accordingly, 15 female athletes were allocated to the highly trained and 13 to the moderately trained group (HT = 1.47 ± 0.22 vs. MT = 1.05 ± 0.16;

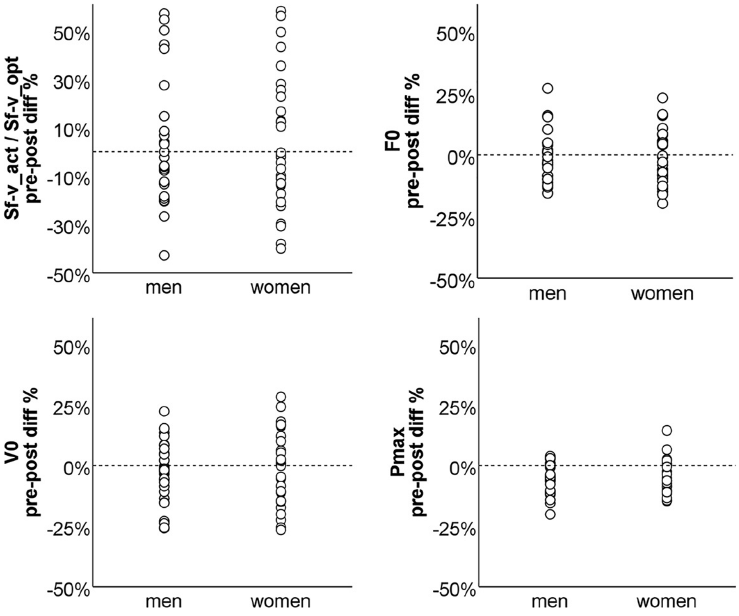

Fig. 2. Individual changes of the FV profile from pre to post exercise. S_{fv}_act/S_{fv}_opt: ratio of the measured to optimal force-velocity slope (upper left panel); F_0 (theoretical maximum force) (upper right panel); v_0 (theoretical maximum velocity) (lower left panel); P_{max} (theoretical maximum power) (lower right panel). Dashed horizontal lines represent zero changes from pre- to post-exercise

Table 4. Changes in the force-velocity profile before and after the exercise for highly and moderately trained participants (mean±*SD*)

	Variables	Group	Pre exercise	Post exercise	Difference (%)	Repeated measures ANOVA
Men	F_0 $(N\ kg^{-1})$	HT	34.9 ± 3.2	34.4 ± 2.7	−1.0 ± 8.7	F (1, 26) = 0.001;
		MT	32.8 ± 3.5	32.2 ± 3.5	−1.0 ± 11.5	$P = 0.97$; $\eta_p^2<0.00$
	v_0 $(m{\cdot}s^{-1})$	HT	3.0 ± 0.5	2.8 ± 0.4	−5.1 ± 11.6	F (1, 26) = 0.92;
		MT	2.7 ± 0.6	2.7 ± 0.6	−1.1 ± 14.4	$P = 0.34$; $\eta_p^2 = 0.03$
	P_{max} $(w\ kg^{-1})$	HT	25.9 ± 3.3	24.0 ± 2.9	−7.0 ± 6.2	F (1, 26) = 3.64;
		MT	22.0 ± 2.9	21.3 ± 2.9	−3.3 ± 5.2	$P = 0.07$; $\eta_p^2 = 0.12$
	S_{fv}_act/S_{fv}_opt	HT	0.9 ± 0.2	0.9 ± 0.2	6.5 ± 27.5	F (1, 26) = 0.45;
		MT	0.9 ± 0.3	0.9 ± 0.2	−0.3 ± 24.3	$P = 0.51$; $\eta_p^2 = 0.02$
Women	F_0 $(N\ kg^{-1})$	HT	37.6 ± 5.3	37.2 ± 3.8	−0.2 ± 10.4	F (1, 26)<0.00;
		MT	32.0 ± 3.7	31.6 ± 2.1	−0.4 ± 11.2	$P = 0.99$; $\eta_p^2<0.00$
	v_0 $(m{\cdot}s^{-1})$	HT	2.5 ± 0.3	2.4 ± 0.3	−4.0 ± 12.7	F (1, 26) = 0.01;
		MT	2.6 ± 0.4	2.5 ± 0.4	−2.1 ± 18.0	$P = 0.92$; $\eta_p^2<0.00$
	P_{max} $(w\ kg^{-1})$	HT	22.0 ± 2.9	21.8 ± 3.2	−5.3 ± 5.7	F (1, 26) = 0.31;
		MT	20.3 ± 3.0	19.4 ± 3.1	−4.2 ± 8.2	$P = 0.59$; $\eta_p^2 = 0.01$
	S_{fv}_act/S_{fv}_opt	HT	1.1 ± 0.2	1.1 ± 0.2	5.2 ± 25.7	F (1, 26) = 0.22;
		MT	0.9 ± 0.2	0.9 ± 0.2	2.4 ± 31.4	$P = 0.64$; $\eta_p^2<0.01$

HT: highly trained; MT: moderately trained (based on the one-repetition maximum normalized to body weight). F_0: theoretical maximum force; v_0: theoretical maximum velocity; P_{max}: theoretical maximum power; S_{fv}_act: slope of measured force-velocity relationship; S_{fv}_opt: slope of optimal force-velocity relationship.

$P < 0.001$). The repeated measures ANOVA did not reveal differences in their changes in any of the examined FV profile measures, both strength expertise groups had changes of similar direction and magnitude after the exercise protocol (Table 4).

DISCUSSION

The aim of this study was to investigate the effects of a high-load resistance exercise protocol on the force-velocity profile in resistance-trained women and men. The most important finding was that the exercise protocol decreased power output, but without significant changes in the participants' individual force-velocity profile. Men and women demonstrated similar changes in both unloaded jumps and in their FV profile.

Unloaded vertical jumps have been used frequently to monitor neuromuscular readiness and fatigue [1] with most studies reporting significant decrease in vertical jump performance after an acute training load. For instance, Rodacki et al. [2] reported a mean decrease in jump height of ~14% when fatiguing the knee extensor and ~6% when fatiguing the knee flexor muscles. In a similar study [3], vertical jump performance decreased by ~8% when using multiple lower-body exercises. In our study the difference in vertical jump height between the pre and post exercise conditions was ~6% and it was similar for both men and women. This lesser difference compared to the ones reported in the literature [2, 3] may be attributed to the type of the exercise protocols, which in both studies included repetitions until failure. In this study we applied a submaximal exercise protocol (~85% of 1RM), with a predefined, controlled number of sets and repetitions (5 × 3). In weightlifting, this load is often used to maximize effectiveness of training by targeting strength and velocity improvement simultaneously. Repetitions during the sets are limited to three and are applied with buffer aiming at preventing maximal fatigue and thus a significant decrease in velocity. Total volume was also submaximal, at the middle of the optimal repetition range used during Olympic weightlifting and strength training [27]. Optimal repetition range in weightlifting is considered around 1-3 repetitions in 3–5 sets and aims to improve both speed and strength [20]. This range extends from minimal effective volume to maximum adaptive volume. Minimal effective volume refers to the threshold in training load that may induce training adaptations and thus improvement, whereas maximal adaptive volume refers to the highest training load, which may be performed without overstimulating the muscles [28]. Not surprisingly, changes in jump performance in response to a submaximal resistance training protocol were smaller compared to exercise protocols of maximal fatigue.

Loaded jumps and FV profile assessment can provide further insights into the mechanical properties of muscle beyond those obtained with only unloaded jumps. It has been reported recently that changes in FV profile following an acute training protocol depend on the applied training load [13]. High training loads induce a significant decrease in force, whereas low loads have the same effect on velocity. Based on the above, we assumed that the high training load (~85% of 1RM) we used in this study would shift the FV profile towards force deficit. The results, however, did not confirm our assumption. The FV profile did not change after the exercise protocol. Despite the lack of changes in the FV profile, performance in vertical jump decreased significantly after the exercise. This is an interesting finding considering that the FV profile has been proposed to influence performance in vertical jumping independently from maximal power output [24]. The exercise protocol decreased power output during both unloaded and loaded jumps, indicating significant loss in explosiveness, but without altering the FV profile. In addition, there was an unexpected decrease of medium effect size in v_0 in both genders, which challenges the assumption that high training load affects force generating ability, but not velocity [13]. Reduction in velocity is usually attributed to impairments in neural input, which is indicative of central fatigue [2], and it seems that it may be also affected by a high-load exercise. Overall, these findings suggest that the sensitivity of the FV profile to detect changes in response to an acute training protocol warrants further investigation.

The complexity of the FV profile is further indicated by the large inter-individual variability. All the participants performed the same training protocol at the same relative intensity. Yet, changes in their FV profiles were inconsistent, indicating that besides the training load, other factors such as muscle fiber type, resistance to fatigue, and hormonal metabolism may also account for the changes in FV profile. An important consideration is the possible variation in fatigue levels experienced after the exercise. Despite the same relative intensity, the exercise protocol likely did not result in identical fatigue for all participants, which may provide a simple explanation for the large individual heterogeneity. Nevertheless, changes in the FV profile in response to an acute exercise may provide new insights into neuromuscular abilities and further individualization in loading strategy during resistance training beyond that provided from FV profile assessment in unfatigued condition. Larger decreases in force would verify maximal strength training needs, while those experiencing larger decreases in velocity may benefit from smaller external loads or from longer rest periods between sets during their resistance training.

Regarding sex differences, previous reports have suggested that women have greater fatigue resistance than men, particularly in exercise protocols of submaximal intensity [14]. The main mechanisms described in the literature to explain the differences in muscle fatiguability between men and women have been related to muscle mass, substrate utilization, muscle morphology and neuromuscular activation [14]. Considering the exercise protocol used in this study, we hypothesized that muscle mass and the concurrent force production may have a key role behind the ability to maintain force output after the exercise protocol. While working at the same relative intensity, absolute load and thus total force exertion was less for women resulting in less muscle oxygen demand and potentially in less fatigue. This would mean larger decrements in force for men than for women. Our findings can only partly confirm this idea, since female athletes in this study exhibited smaller decrease in force production after the exercise intervention in vertical jumps against low to moderate external loads. This may be explained with better muscle perfusion in women compared with men at low-intensity muscle contractions, as it has been suggested in the literature [4]. However, beside this single difference, the results rather indicate analogous response to the applied acute exercise stimulus for men and women and are in line with the reports of Dinyer et al. [16] and Keller et al. [17], who found similar changes in neuromuscular performance after an acute exercise between men and women.

The absence of any effects of the total training load (expressed as tonnage load) is further supported by the analysis according to the initial strength level. The individual 5RM was used to estimate the 1RM in back squat and then to divide participants in two subgroups as described earlier (highly and moderately trained). Performance in 5RM provided the basis for the external loads used during the exercise protocol. Higher 5RM was paired with larger loads. This denoted the same relative, but different absolute intensities for the participants. It was assumed that larger exercise loads would increase muscle fatiguability and accordingly would result in larger changes in force or velocity (or both). We expected, therefore, that the highly trained group would demonstrate larger decrease in force after the exercise and accordingly a shift of the FV profile towards force deficit. The results, however, did not support this assumption (Table 4): both subgroups (highly and moderately trained) had very similar changes in the FV measures examined. These findings again indicate that tonnage load is not associated with changes in the FV profile and may indirectly imply that maximal dynamic strength has no impact on how the FV profile changes in response to an acute exercise.

In this study we examined the effects of an acute training protocol, but without quantifying fatigue. The lack of fatigue measures limits our understanding on how FV profile changes in response to a training load. In future studies, changes in the FV profile should be examined under similar fatigue conditions achieved by individualizing the training protocol (e.g. adjusting the number of repetitions, sets, or resting periods). Further, we did not consider the menstrual cycle for our female participants. Hormonal changes during the menstrual cycle may influence the response to training, which needs to be considered during the interpretation of the results.

CONCLUSIONS

Findings highlight the complexity of the FV profile to monitor changes in response to an acute resistance exercise. The results suggest (1) that the exercise protocol decreased vertical jump performance and maximal power output without a concomitant change in FV profile, (2) large interindividual variability in FV profile changes ranging from notable decrease to notable increase following the exercise, and (3) that absolute training load is not associated with the changes in any of the FV profile measures.

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