Influence of sex and strength differences on the load–velocity relationship of the Smith-machine back squat

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Abstract

Purpose We aimed at determining whether the load–velocity relationship of the Smith machine concentric-back squat differs between sexes and persons with different levels of strength.

Methods Thirty-two participants (16 males: 23.3 ± 3.8 years and 16 females: 26.1 ± 2.7 years) were included. Load and mean concentric velocity (MCV) were obtained individually during an incremental test (30–90% one-repetition maximum—1RM).

Results We obtained strong linear relationships between the individual MCV and relative load ($R^2 > 0.95$). Overall, relatively strong persons reached faster MCVs throughout the full range of relative loads (effect size [ES]: 0.48–0.93), except at 1RM. We also obtained steeper slopes and higher velocity intercepts (y intercepts) in relatively strong participants (ES: 0.05 and 0.83, respectively; $p < 0.01$). Finally, we found that males attained steeper load–velocity relationships (ES favoring relatively strong and weak males: 2.8 and 1.4, respectively) and higher velocity intercepts (ES favoring relatively strong and weak males: 2.0 and 1.0, respectively) than females ($p < 0.0001$).

Conclusion MCV can be used to estimate relative load on the Smith machine concentric-back squat in males and females with different levels of muscle strength; however, the load–velocity relationship is affected by muscle strength and sex. Therefore, the extraction of individual load–velocity relationships is advisable instead of computing group estimations.

Keywords Sexual dimorphism · Resistance exercise · Training · Lower limb

Abbreviations

ANOVA   Analysis of variance
MCV   Mean concentric velocity
1RM   1 repetition maximum

Introduction

The prescription of resistance training based on the direct determination of one-repetition-maximum (1RM) remains popular among fitness and sports professionals. Despite being of high practical value, the continued use of relative loads from a baseline 1RM might compromise adaptations

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because increases in maximal strength with training can occur rapidly [1]. Moreover, 1RM determination is not feasible for group testing (e.g. team sports) and is largely influenced by a plethora of energetic, neural and muscular factors, as well as by general lifestyle [2]. To overcome some of these limitations, the load–velocity relationship has been introduced in the field of resistance training. This methodology relies on the strong level of relationship between exercise load and movement velocity and can be used to predict the 1RM [3–5].

There is general agreement that movement velocity is strongly related with relative load in response to several resistance exercises ($R^2 > 0.95$) [6, 7]. However, it is important to note that past research focused primarily on data derived from male participants [8, 9]. In specific, and that we know of, females were only included in five previous studies that aimed at characterizing sex differences in response to the military press, bench-press, leg press and back squat using a Smith machine [10–14]. The authors observed that the relationship between movement velocity and relative load in these exercises is exceptionally strong in both sexes ($R^2 > 0.85$). Yet, it was additionally reported that males tend

to have a steeper load–velocity relationship, as well as faster movement velocities in response to several relative loads for all these exercises [10–14]. Ultimately, these data provide preliminary evidence that sex affects both the upper- and lower-limb load–velocity relationship and that the estimation of relative load based on velocity should be sex specific.

Past research has shown that, besides differing between sexes, the load–velocity relationship varies as a function of muscle strength and can change after a four-week resistance training program [14–16]. Therefore, different levels of muscle strength between males and females may confound sex comparisons in the load–velocity relationship. Unfortunately, this specific aspect has not yet been examined at the level of lower-limb exercise (e.g. back squat). Thus, the aim of this study was twofold: (i) to compare the load–velocity relationship between sexes, separately for relatively strong and weak individuals, during lower-limb exercise (i.e. Smith-machine back squat), and to (ii) examine the influence of different strength levels on the load–velocity relationship in squatting (using a mixed population of males and females grouped by strength level category). We hypothesized that there would be a strong linear relationship between relative load and velocity for both sexes in squatting. Also that the load–velocity relationship for the Smith-machine back squat would be consistently different between males and females (both in relatively weak and strong individuals). Finally, that the load–velocity relationship of the Smith-machine back squat would differ between a mixed population of relatively strong and weak individuals (steeper slope and with larger velocity intercepts in relatively strong persons).

Materials and methods

Participants

We studied 32 young healthy adults on no medications (16 males: 23.3 ± 3.8 years; 75.9 ± 9.4 kg; 178.7 ± 5.3 cm and 16 females: 26.1 ± 2.7 years; 56.3 ± 5.8 kg; 162.6 ± 5.6 cm). All participants were active, accumulating 9 h of physical activity per week as part of their academic work. They were all well accustomed to resistance training and to the back squat exercise (training frequency of at least 2–3 times per week). None of the females included in this study was pregnant or using oral contraceptives at the time of testing. In addition, they all had self-reported regular menstrual cycles of ~ 28 days. Participants were non-obese, non-smokers, and free from any known cardiovascular, metabolic, respiratory, and orthopedic diseases as assessed by a health-screening questionnaire. The risks involved in the experimental design were carefully explained to each participant and informed consent was obtained from all individual participants included in the study. The study complied with the principles

set forth in the Declaration of Helsinki and was approved by the Faculty's Ethics Committee (CEFMH Nº 16/2021).

Design and procedures

All testing sessions were performed between 08:00 and 12:00 h, in a laboratory at a temperature between 22 and 24 °C and a relative humidity between 44 and 56%. Participants were asked to avoid physical exercise for at least 24 h before each session. During the first testing session, body mass and height were measured with the participants wearing lightweight clothes and no shoes. Height was obtained using a stadiometer to the nearest 0.5 cm (Secca 216—Hamburg, Germany). Body mass was measured on a digital scale to the nearest 0.01 kg (TANITA® BF-350 body composition analyzer, Arlington Heights, IL). This initial session also had the purpose of familiarizing each participant with the concentric phase of the back squat. Therefore, the participants completed 5 sets of 5 back-squat repetitions on a Smith machine (Matrix Fitness® G1 Smith machine, WI, USA) and on each set the load on the bar was incremented so that the participants could be familiarized through a varied range of loads and with the concentric phase being performed as fast as possible. On the second testing session (72 h after the first testing session), a concentric back-squat protocol with progressive increments of loading was conducted until the actual 1RM was directly determined with the completion of a single maximal lift. Each repetition began with the participants thighs parallel to the floor and ended in a high-bar concentric-back squat position. Testing was conducted on the same Smith machine used for the familiarization session and all repetitions were performed at maximal intended velocity throughout the full range of motion.

Load–velocity relationship

A brief warm up preceded testing. The warm up consisted of 5 min of unloaded cycle ergometry (Monark Ergomedic 828E cycle ergometer, Monark Exercise AB, Vansbro, Sweden), followed by 3 sets of 10 callisthenic full squats. Then, for the specific warm up, each participant completed 3 sets of 5 repetitions on the Smith machine with an unloaded bar and with the concentric phase being performed as fast as possible. Squatting was performed barefoot (to ensure similar conditions between participants), with feet shoulder width apart or slightly wider and vertically aligned with the bar. The bar rested on the upper trapezius and the movement started in the bottom of the squat position, which ensured that all participants had their thighs as parallel to the floor as possible. From this position, the participants were instructed to complete the concentric phase of the lift as fast as possible until full extension was attained at the hip and knee joint. The heels were allowed to lift off from the floor but jumping

was not allowed. The hip range of motion during each lift was not accounted for. However, since the barbell rested on the upper trapezius of each participant during testing, individual differences in hip flexion during exercise were mild and strictly related with anthropometric factors. Between each repetition, the participants had to hold the bottom position for at least 3 s to ensure that the eccentric phase would not interfere with their concentric performance. According to past research, imposing a pause between the eccentric and concentric phases of the back squat (i.e. stop-back squat) increases the reliability of strength assessments when using a Smith machine [17]. The bottom position hold was completed with the barbell resting on the Smith machine's safety bars to make sure that it did not cause excessive and undue fatigue. The load was progressively incremented until 1RM was determined directly with the completion of a single maximal lift. Also, no training accessories were allowed (weightlifting belts, knee sleeves, etc.).

All participants began the progressive loading protocol with an unloaded bar and subsequent increments were based on the individual body mass. The second load was set at 20% of body mass and additional increments of 20% were added until reaching a bar mean concentric velocity (MCV) equivalent to 0.70 m.s^{-1}. From then on, the loading increments varied between 2.5 and 10 kg until 1RM was finally achieved. When approaching 1RM, load increments were set by a skilled investigator after reaching a consensus with the participant. For lighter (MCV > 1.15 m.s^{-1}), medium (0.70 > MCV > 1.15 m.s^{-1}) and heavy loads (MCV < 0.70 m. s^{-1}), the number of attempts varied between 3–5, 2–4 and 1–2, respectively [18]. MCV was taken from the start of the concentric phase of each lift to the instant corresponding to the maximum height of the bar, with a previously validated Chronojump linear position transducer, which sampled the bar's velocity at a frequency of 1000 Hz (Chronojump, Barcelona, Spain) coupled to the Smith machine [19]. MCV was chosen instead of mean propulsive velocity and peak velocity because it shows a stronger relationship with relative load in response to squatting ($R^2 = 0.96$) [18, 20]. The inter-set pause corresponded to 3 min. The pause between repetitions in each set was consistently < than 5 s and only the fastest attempt for each load was recorded. According to past research, the ICCs of the Smith machine stop back squat is consistently > 0.90 for relative loads < 80% 1RM. In addition, the coefficient of variation for the whole load–velocity relationship of this specific exercise corresponds to 2.9% [17].

Statistical analysis

In past research, it was shown that sample sizes between 3 to 9 participants allow the detection of sex differences in muscle strength and velocity values [14, 21]. Despite this, we computed a sample size calculation to ensure the achievement of enough statistical power to draw accurate conclusions using sample data. Based on the available literature, the difference in the slope of the load–velocity relationship between males and females for the bench-press exercise is characterized by a Cohen's f of 0.545 [14]. Thus, a sample size of 32 participants (16 males and 16 females) was estimated to achieve more than 80% power of correctly rejecting the null hypothesis (G*Power software, version 3.1.9.2).

Male and female participants were classified as relatively strong and weak based on their relative 1RM for the concentric-back squat. The median values of relative 1RM in both sexes were used as a cut-offs to enable this discrimination. In specific, participants scoring above and below the median values for each sex were classified as relatively strong and weak, respectively. As such, readers should consider that adjectives such as "stronger" or "strong", "weaker" or "weak" that are further mentioned, are related to relative and not absolute strength values. Before computing between-group comparisons, data were tested for normality and homogeneity of variance with the Shapiro–Wilk and Levene's test, respectively. The MCVs and relative loads obtained for each participant were used to extract the individual slope (rate of change in MCV as a function of relative load) and y intercept (predicted MCV in response to unloaded concentric-back squat). Past research has shown that movement velocity at 100% 1RM should not be incorporated when the load–velocity relationships are created from MCV [17, 22–24]. It has not yet been determined whether this is sustained for the concentric-back squat performed on a Smith machine. For this reason, we used two different approaches to compute the individual load–velocity relationships: MCVs and relative loads up to 90% 1RM vs. MCVs and relative loads up to 100% 1RM. Such individual load–velocity relationships were computed using linear regression models and R^2 was used to assess their level of adjustment. Subsequently, we compared the Fisher's Z transformed R coefficients obtained with both approaches using paired t tests. We then selected the approach resulting on individual load–velocity relationships with higher R coefficients for all subsequent analyses. In addition, as a complementary analysis, we also extracted general load–velocity relationships for male and female participants within each strength level category (i.e. relatively strong and weak).

A two-way ANOVA (with strength level and sex as between factors) was conducted on the Fisher's Z transformed R coefficients to explore possible main effects and interactions. The MCVs at seven relative loads (30, 40, 50, 60, 70, 80 and 90%1RM) were obtained from the individual load–velocity relationship, through their respective first-order polynomials [20]. Two-way ANOVAs (with strength level and sex as between factors) together with the Hedges' g effect size (with its 95% confidence interval

displayed in forest plots) were used to explore the impact of different strength levels and sex on the dependent variables. The Hedges' g effect size was interpreted as follows: trivial < 0.2, small 0.2–0.6, moderate 0.6–1.2, large 1.2–2.0 and extremely large > 2.0 [18]. The ANOVA's eta-squared values (proportion of total variance that is attributable to an effect) are reported for significant findings (small, medium and large effect: 0.01, 0.06 and 0.14, respectively) [8]. The described ANOVAs were conducted on the individual relationships, not on the general load–velocity relationships plotted by groups. Data analyses were performed using SPSS software version 27.0 (SPSS Inc., Chicago, IL, USA) and statistical significance was set at $p < 0.05$.

Results

The median value of relative 1RM for males and females was 1.22 and 1.13, respectively. Based on these cut-off values, the participants were grouped as relatively strong (relative 1RM > median value) and weak (relative 1RM < median value) (Tables 1 and 2). As depicted in Tables 1 and 2, relatively strong participants showed higher values of absolute (strength-level main effect: $F = 66.9$, $p < 0.0001$; $\eta^2 = 0.71$) and relative 1RM (strength-level main effect: $F = 75.3$, $p < 0.0001$; $\eta^2 = 0.73$). In contrast, there were no strength-level main effects for MCV at 1RM ($F = 0.06$, $p = 0.81$).

Males attained greater absolute 1RM for the concentric-back squat than females (sex main effect: $F = 54.4$; $p < 0.0001$; $\eta^2 = 0.66$). However, this was not sustained for relative 1RM ($F = 3.8$, $p = 0.06$). Males also attained higher MCVs at 1RM compared to that seen in females (sex main effect: $F = 6.8$; $p = 0.014$; $\eta^2 = 0.20$) (Tables 1 and 2). As can be seen in Fig. 1 A and B, the standardized mean difference in MCV at 1RM between sexes was of moderate magnitude (effect size: 0.69 and 1.15, favoring relatively strong and weak males, respectively). No strength level-by-sex interactions were obtained for the analyzed variables.

Overall, the Fisher's Z transformed R coefficients obtained with the individual load–velocity relationships up to 90% 1RM were higher than the ones obtained with relative loads up to 100% 1RM (up to 90% 1RM: 3.0 ± 0.7 vs. up

Table 1 Absolute and relative values of one-repetition maximum (1RM) for the concentric-back squat using a Smith machine in relatively strong participants of each sex

	Relatively strong		
	All ($n = 16$)	Males ($n = 8$)	Females ($n = 8$)
Concentric Smith machine back squat			
1RM (kg)[#,*]	99.5 ± 23.3	117.2 ± 17.8	97.8 ± 24.2
Relative 1RM[#]	1.47 ± 0.19	1.51 ± 0.16	1.43 ± 0.22
Actual 1RM MCV (m.s⁻¹)*	0.25 ± 0.08	0.27 ± 0.09	0.22 ± 0.05
Velocity intercept (m.s⁻¹)[#,*]	1.30 ± 0.13	1.41 ± 0.09	1.20 ± 0.07
Slope (m.s⁻¹. %RM⁻¹)[#,*]	− 0.010 ± 0.001	− 0.011 ± 0.001	− 0.009 ± 0.001

The associated mean concentric velocity (MCV) during squatting, as well as the load–velocity relationship (velocity intercept and slope) using individual linear regression analysis are also shown

Values are mean ± standard deviation. Relative 1RM corresponds to the 1RM to bodyweight (kg) ratio

*Sex main effect ($p < 0.05$)

[#]Strength-level main effect ($p < 0.05$)

Table 2 Absolute and relative values of one-repetition maximum (1RM) for the concentric-back squat using a Smith machine in relatively weak participants of each sex

	Relatively weak		
	All ($n = 16$)	Males ($n = 8$)	Females ($n = 8$)
Concentric Smith machine back squat			
1RM (kg)[#,*]	64.7 ± 16.2	81.9 ± 11.5	50.9 ± 6.9
Relative 1RM[#]	0.99 ± 0.12	1.06 ± 0.09	0.93 ± 0.12
Actual 1RM MCV (m.s⁻¹)*	0.24 ± 0.08	0.28 ± 0.08	0.20 ± 0.06
Velocity intercept (m.s⁻¹)[#,*]	1.17 ± 0.14	1.25 ± 0.14	1.09 ± 0.08
Slope (m.s⁻¹. %RM⁻¹)[#,*]	− 0.009 ± 0.001	− 0.010 ± 0.001	− 0.009 ± 0.001

The associated mean concentric velocity (MCV) during squatting, as well as the load–velocity relationship (velocity intercept and slope) using individual linear regression analysis are also shown

Values are mean ± standard deviation. Relative 1RM corresponds to the 1RM to bodyweight (kg) ratio

*Sex main effect ($p < 0.05$)

[#]Strength-level main effect ($p < 0.05$)
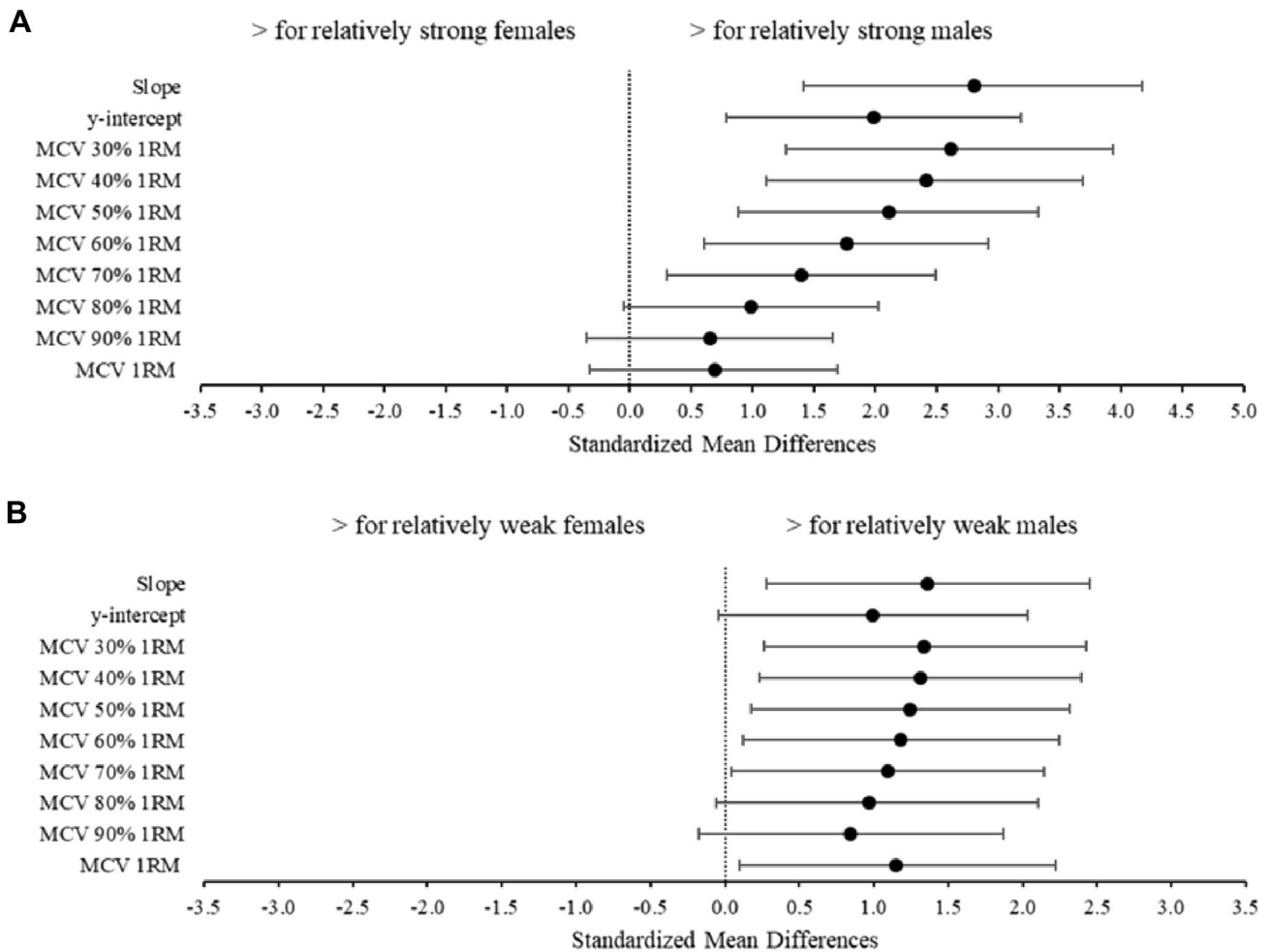
Fig. 1 Standardized mean differences (Hedges g's and their corresponding 95% confidence intervals) in the individual load–velocity relationship between sexes categorized by strength level: **A** relatively strong participants and **B** relatively weak participants. Slope and velocity intercept were obtained from load–velocity relationships from 30 to 90% of one-repetition maximum (1RM). Mean concentric velocity (MCV) is reported for relative loads from 30 to 100% of 1RM

to 100% 1RM: 2.8 ± 0.6, $p = 0.007$). For this reason, all subsequent analyses were performed on individual load–velocity relationships up to 90% 1RM. The ANOVA computed on the Fisher's Z transformed R coefficients of the individual profiles resulted in no main effects of strength level ($F = 0.5$, $p = 0.624$) or interaction ($F = 1.0$, $p = 0.318$), but revealed significant effect for sex, favoring males ($F = 6.1$, $p = 0.020$) (Fig. 2). We also obtained strong linear relationships between relative load and MCV ($R^2 > 0.90$) for the general load–velocity relationships, with the exception of that seen in relatively weak females (Fig. 3A and B).

Tables 1 and 2 show that relatively strong participants exhibited a steeper load–velocity relationship ($F = 16.2$, $p = 0.009$; $\eta^2 = 0.22$) and higher velocity intercepts than their relatively weak counterparts ($F = 13.9$, $p = 0.001$; $\eta^2 = 0.33$). The magnitude of standardized mean differences between relatively strong and weak participants corresponded to

0.95 and 0.83 for slope and velocity intercept, respectively (moderate effect size) (Fig. 4). Overall, males also attained a steeper load–velocity relationship (sex main effect: $F = 16.2$; $p < 0.0001$; $\eta^2 = 0.36$) and higher velocity intercepts than females (sex main effect: $F = 28.7$; $p < 0.0001$; $\eta^2 = 0.51$). As depicted in Fig. 1A and B, for the slope of the load–velocity relationship, the standardized mean difference between sexes favored males and ranged from large to an extremely large effect (effect sizes: 1.4 and 2.8 for between-sex comparisons in relatively weak and strong participants, respectively). For the velocity intercept, the standardized mean difference also favored males but with a magnitude of effect that varied from moderate to large (effect sizes: 1.0 and 2.0 for between-sex comparisons in relatively weak and strong participants, respectively).

Finally, as shown in Fig. 1A and B, the load–velocity relationship of males was characterized by faster MCVs

Fig. 2 Pearson's coefficients of correlation (median and range) obtained from the individual load–velocity relationships. *R. strong* relatively strong, *R. weak* relatively weak
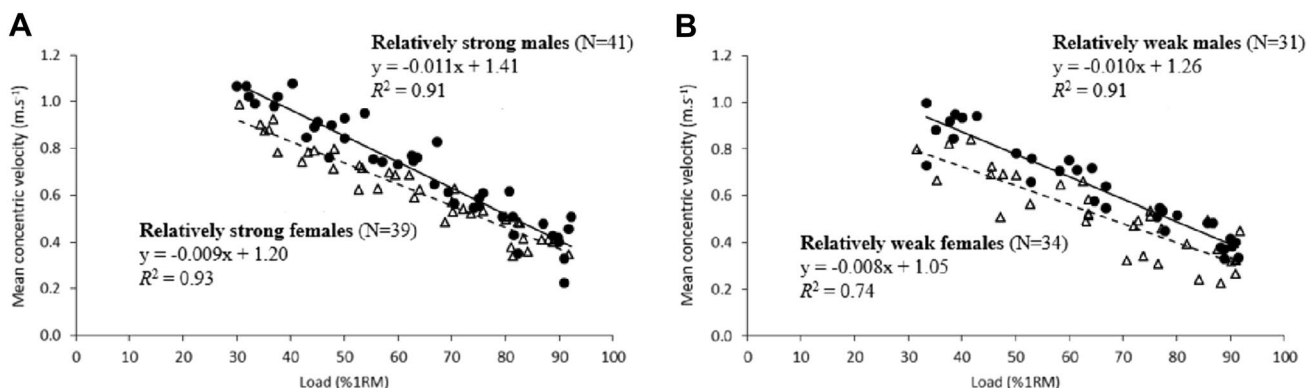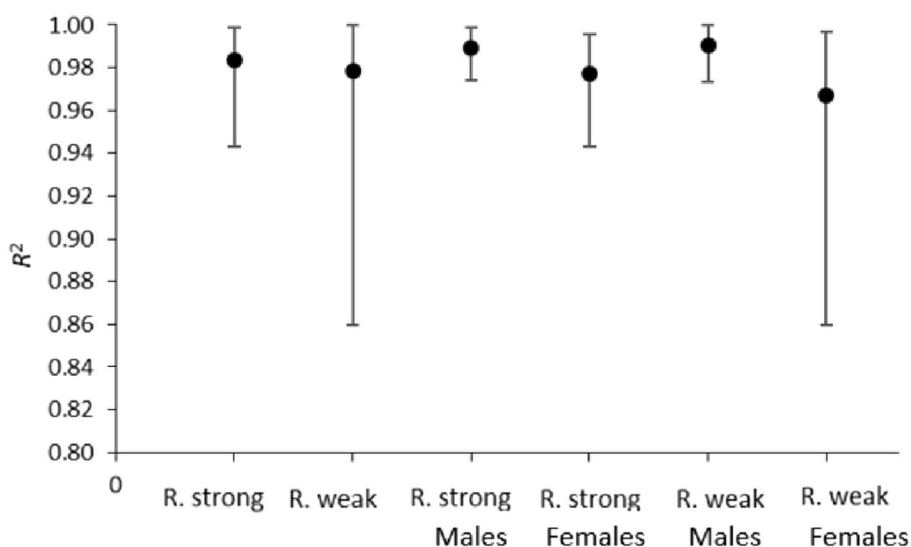

Fig. 3 General load–velocity relationship for **A** relatively strong males vs. relatively strong females and **B** relatively weak males vs. relatively weak females. The black circles and white triangles represent males and females, respectively. N translates the number of assessments in the analysis and R^2 is the Pearson's coefficient of determination. The linear regression equations obtained for the general load–velocity relationship in males and females are also shown

throughout the full spectrum of relative loads. Furthermore, the magnitude of sex difference was larger for comparisons between relatively strong (moderate to extremely large effect sizes: 0.7–2.6) than relatively weak participants (moderate effect sizes: 0.8–1.3). Yet, as can also be seen, the standardized mean difference in MCV between sexes was progressively attenuated from lighter to heavier relative loads (independently of strength level).

Discussion

The main findings of this study can be summarized as follows. First, the individual relationship between relative load and MCV is strongly linear for the Smith machine concentric-back squat (in persons with different strength levels and in both sexes). Second, we also found that a mixed sample of relatively strong males and females shows greater velocity intercepts and a steeper load–velocity relationship than their relatively weak counterparts. Third, despite showing faster MCVs in response to several submaximal relative loads, relatively strong individuals complete 1RM at similar MCV as relatively weak persons. Fourth, males exhibit an overall steeper load–velocity relationship than females, as well as larger velocity intercepts and faster MCVs at all relative loads (including at 1RM). Yet, sex differences in MCV are particularly larger for comparisons between relatively strong males vs. relatively strong females.

We obtained strong linear relationships between the individual MCVs and relative loads for persons with different strength levels and sex. These data are well aligned with past research showing that the R^2 for the load–velocity relationship obtained during upper- (i.e. bench-press, bench-pull and pull-up exercise) and lower-limb exercise (i.e. squat and
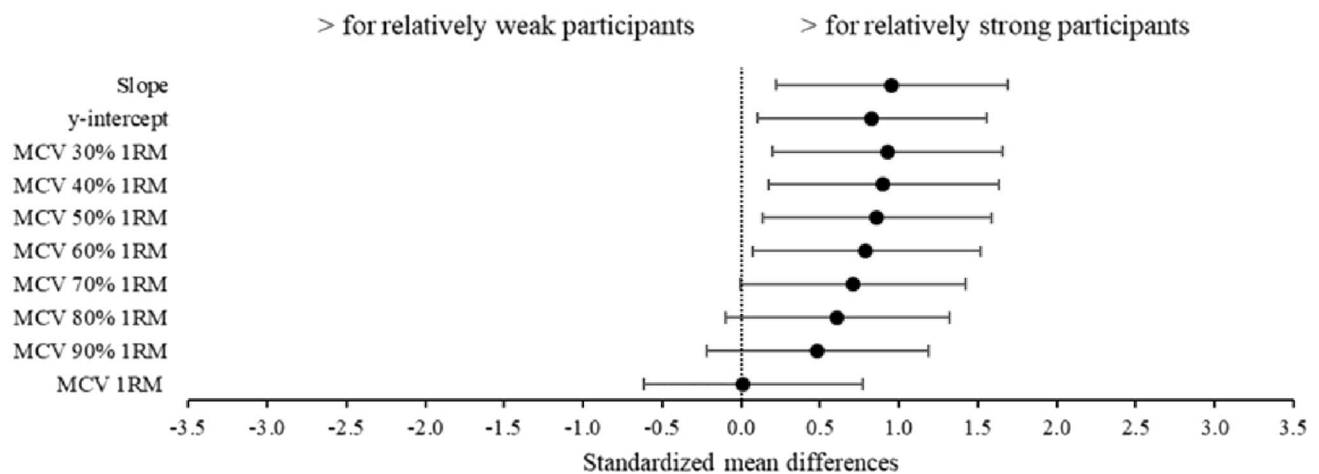
Fig. 4 Standardized mean differences (Hedges' g and their corresponding 95% confidence intervals) in the individual load–velocity relationship between relatively strong and relatively weak participants. Slope and velocity intercept were obtained from load–velocity relationships from 30 to 90% of one-repetition maximum (1RM). Mean concentric velocity (MCV) is reported for relative loads from 30 to 100% of 1RM

vertical jumps) is typically ≥ 0.85 [14, 15, 18, 25]. In addition, our analyses indicate that the strength of the linearity of the relationship between MCV and relative load decreases when incorporating the MCV at 100% 1RM. These findings are similar to that reported in past research examining the load–velocity relationship in other multi-joint resistance training exercises [17, 22–24]. Taken together, it can be concluded that, for the back squat exercise (i.e. Smith machine and free weight), MCV at 1RM should not be included in the set of velocities that make up the load–velocity relationship.

Contrasting with that seen with the individual analyses, we obtained lower R^2 values for relatively weak females when plotting the general load–velocity relationship ($R^2 = 0.74$). Past research has indicated that data fit in the general load–velocity relationship is affected by the fact that more than one observation from the same participant is used for calculations [26]. This lower R^2 value may also be explained by higher levels of heterogeneity among weaker women, but a larger sample size would be necessary to confirm this claim. It has also been proposed that the determination of the individual load–velocity relationship overcomes these limitations by improving the quality of estimations and our findings are in agreement with this concept [23, 27].

Data computed for relatively strong and weak participants were contrasted using a mixed sample of males and females, grouped by strength-level category (relatively strong vs. relatively weak). We found that relatively strong individuals achieved higher MCVs throughout the full spectrum of submaximal relative loads. This indicates that the concentric-back squat load–velocity relationship is partially related to maximal strength. It is interesting to note that these findings diverge from some reported on upper-limb exercises [7, 9, 14]. In those studies, mean velocity achieved by relatively

strong individuals was lower (i.e. bench press) or similar (i.e. pull up) to that reached by relatively weak persons [7, 9].Taken together, it can be concluded that, besides being affected by several other factors (e.g. type of exercise and execution technique) [6, 17], the submaximal continuum of the load–velocity relationship is also highly specific to the exercised body part.

As shown in two previous reports [7, 9], no differences were observed between relatively strong and weak participants for MCV at 1RM (~ 0.24 m.s^{-1}). Ultimately, this substantiates the use of a general minimum velocity threshold (independently of strength level) to simplify the determination of 1RM in the Smith machine concentric-back squat. In a recent study on the Smith-machine bench-press exercise, it was shown that a novel minimum velocity threshold (i.e. optimal minimum velocity threshold) displays a high level of reliability and accuracy for estimating the 1RM [23]. Whether these findings hold true for the Smith-machine back squat remains largely unknown at this stage. In addition, despite the promising results of this novel approach, it should be noted that still implicates the a priori determination of the 1RM to begin with, which limits the practicality of the predictive method. Furthermore, in our study, the slope of the load–velocity relationship was also steeper for relatively strong participants (moderate effect size). Therefore, based on our findings, muscle strength is also a fundamental determinant of the rate of change in MCV with respect to relative load during the Smith machine concentric-back squat.

The available literature provides compelling evidence that, for upper- and lower-limb exercise (i.e. bench press, military press, leg press and Smith machine back squat), the load–velocity relationship follows a sexually

dimorphic pattern [10–13]. However, while four of these studies found that males reach faster MCVs throughout the full spectrum of submaximal relative loads, this is not a universal finding [10–13]. For instance, in another study it was shown that, while the bench-press performance in males reached faster velocities during light lifts, the opposite occurred for heavier lifts (faster for females) [14]. Contrasting with the results of this last study, we found that during lower-limb exercise (i.e. Smith machine concentric-back squat), males attained faster MCVs throughout the full spectrum of submaximal relative loads and this is similar to that reported for this specific exercise in one previous study [13]. Importantly, these findings were consistent for between-sex comparisons within relatively strong and weak persons and this is novel. In addition, it is relevant to note that, in clear contrast to that seen for comparisons between relatively strong and weak individuals (mixed sample population), sex differences in movement velocity were extensive to MCV obtained at 1RM in both strength categories. Yet, we found that the sexual dimorphism in MCV was progressively attenuated from light (extremely large effect size) to heavy lifts (moderate effect size). These data are in partial agreement with those of one previous study in which sex differences in concentric back squat movement velocity were virtually dissipated beyond 95% of 1RM [13]. However, in that study, males and females were not grouped by categories of muscle strength and mean propulsive velocity was used instead of MCV, which likely explains the observed minor difference. Irrespectively of this, taken together, and considering that sex revealed a main effect on the Fisher's Z transformed *R* coefficients (favoring males), our data indicate that sex exerts a true impact on the load–velocity relationship of the concentric-back squat and that this effect is largely independent of strength differences between males and females. Nevertheless, it should be noted that the magnitude of sex difference in MCV for submaximal relative loads was dependent on the individual strength levels. In other words, this effect was larger for comparisons between relatively strong (moderate to extremely large effect sizes: 0.7–2.6) than relatively weak participants (moderate effect sizes: 0.8–1.3).

The slope of the relationship between relative load and MCV was also steeper in males (large to extremely large effect sizes), which indicates that the rate of loss in MCV for a given change in relative load was less pronounced in females. These findings are well aligned with past research showing that, for lower-limb exercise, males reach faster velocities of isotonic maximal concentric contractions (greater velocity intercepts) [28, 29]. Taken together, we found that between-sex discrepancies in the load–velocity relationship of the concentric-back squat are manifested in

persons with higher as well as with lower levels of muscle strength.

Limitations

This study has, at least, four limitations. First, we did not measure concentric back-squat performance while controlling for the influence of the menstrual cycle in female participants. It is relevant to note that the influence of the menstrual cycle on muscle strength and power remains a highly controversial topic [30, 31]. However, it was recently found that the magnitude of its effects on performance is small compared with the large differences between males and females [32]. Thus, we do not believe that this limitation affected the key aspects of our study. Second, we also did not measure body composition of the participants included in this study and this precluded us from exploring its true impact on the linearity of the load–velocity relationship in both sexes. Third, since we imposed a pause between the eccentric and concentric phase of exercise, our findings are not applicable to other back-squat conditions (i.e. such as those involving the stretch–shortening cycle). However, it has been shown that while the biological within-subject variation for the back squat can be significantly reduced when imposing a pause between the eccentric and concentric phases of each repetition, other relevant mechanical variables associated to the load–velocity profiles remain essentially unchanged (e.g. 1RM, magnitude of the breaking phase, maximal power load) [17]. Nonetheless, it is important to acknowledge that if the movement were to be executed without a pause, steeper load–velocity relationships would be expected for all the analyzed groups. Fourth, the "strong" groups of our study displayed average values of strength, despite still being significantly stronger than their weaker counterparts. In future studies, a sample comprised of powerlifters or other specialized strength athletes might provide additional information as to whether the present findings are sustained even between highly trained males and females.

Conclusions

These findings further support the idea that, for the concentric back squat (performed in a Smith machine), the individual load–velocity relationship should be prioritized in detriment of general equations. On the one hand, the load–velocity relationship is significantly affected by the individual levels of muscle strength. On the other, sex exerts a considerable impact on the load–velocity relationship of young adults within each strength category. Thus, the extraction of individual load–velocity relationships is advisable.

Declarations

Conflict of interest The authors declare that there are no competing interests to declare.

Ethical approval and informed consent This study was approved by the Faculty's Ethics Comittee (CEFMH Nº 16/2021) and all participants signed an informed consent.

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