Load-Velocity Relationship Variables to Assess the Maximal Neuromuscular Capacities During the Back-Squat Exercise

Alejandro Pérez-Castilla, PhD,[†] Ivan Jukic, MSc,[‡] Danica Janicijevic, PhD,[§||¶] Zeki Akyildiz, MSc,[#] Deniz Senturk, MSc,** and Amador García-Ramos, PhD*[†††]

Background: The relationship between the external load lifted and movement velocity can be modeled by a simple linear regression, and the variables derived from the load-velocity (L-V) relationship were recently used to estimate the maximal neuromuscular capacities during 2 variants of the back-squat exercise.

Hypothesis: The L-V relationship variables will be highly reliable and will be highly associated with the traditional tests commonly used to evaluate the maximal force and power.

Study Design: Twenty-four male wrestlers performed 5 testing sessions (a 1-repetition maximum [1RM] session, and 4 experimental sessions [2 with the concentric-only back-squat and 2 with the eccentric-concentric back-squat]). Each experimental session consisted of performing 3 repetitions against 5 loads (45%-55%-65%-75%-85% of the 1RM), followed by single 1RM attempts.

Level of Evidence: Level 3.

Methods: Individual L-V relationships were modeled from the mean velocity collected under all loading conditions from which the following 3 variables were calculated: load-axis intercept (L_0), velocity-axis intercept (v_0), and area under the line ($A_{line} = L_0 \cdot v_0/2$). The back-squat 1RM strength and the maximum power determined as the apex of the power-velocity relationship (P_{max}) were also determined as traditional measures of maximal force and power capacities, respectively.

Results: The between-session reliability was high for the A_{line} (coefficient of variation [CV] range = 2.58%-4.37%; intraclass correlation coefficient [ICC] range = 0.98-0.99) and generally acceptable for L_0 and v_0 (CV range = 5.08%-9.01%; ICC range = 0.45-0.96). Regarding the concurrent validity, the correlations were very large between L_0 and the 1RM strength (r_{range} = 0.87-0.88) and nearly perfect between A_{line} and P_{max} (r = 0.98-0.99).

Conclusion: The load-velocity relationship variables can be obtained with a high reliability (L_0, v_0, and A_{line}) and validity (L_0 and A_{line}) during the back-squat exercise.

Clinical Relevance: The load-velocity relationship modeling represents a quick and simple procedure to estimate the maximal neuromuscular capacities of lower-body muscles.

Keywords: force-velocity relationship; reliability; stretch-shortening cycle; validity, velocity-based training

From [†]Department of Physical Education and Sport, Faculty of Sport Sciences, University of Granada, Granada, Spain, [‡]Sport Performance Research Institute New Zealand (SPRINZ), Auckland University of Technology, Auckland, New Zealand, [§]University of Belgrade, Faculty of Sport and Physical Education, The Research Centre, Belgrade, Serbia, [||]Research Academy of Human Biomechanics, The Affiliated Hospital of Medical School of Ningbo University, Ningbo University, Ningbo, China, [¶]Faculty of Sports Science, Ningbo University, Ningbo, China, [#]Movement and Training Science Department, Gazi University, Ankara, Turkey, **Sports Department, School of Physical Education, Gelişim University, Istanbul, Turkey, and [††]Department of Sports Sciences and Physical Conditioning, Faculty of Education, Universidad Católica de la Santísima Concepción, Concepción, Chile

*Address correspondence to Amador García Ramos, Department of Physical Education and Sport, Faculty of Sport Sciences, University of Granada, Ctra. Alfacar, 21, Granada, 18011, Spain (email: amagr@ugr.es) (Twitter: @amagr).

The authors report no potential conflicts of interest in the development and publication of this article.

This study was funded by the Centro Mixto Universidad de Granada–Mando de Adiestramiento y Doctrina (5/4/20 TR-COMBATE).

DOI: 10.1177/19417381211064603

Maximal force, velocity, and power capabilities frequently constitute a part of many testing batteries.[8,29] Maximal strength is typically defined as the maximum load that can be lifted only once with proper technique (ie, the 1-repetition maximum [1RM]).[19] In addition, maximal velocity capacity is commonly assessed by recording the velocity at which a very light external load is lifted.[24] Finally, maximal power capacity is determined by manipulating the external load until identifying the load that maximizes the power output (power = force × velocity).[1] More recently, the force-velocity (F-V) relationship has been used to estimate the mechanical capacities of the muscles to produce maximal levels of force (force-axis intercept; F_0), velocity (velocity-axis intercept; v_0), and power ($P_{max} = F_0 \cdot v_0/4$). However, there is no consensus regarding the reliability[2,3,5,11] and concurrent validity[2,3] of these F-V relationship parameters. One of the main challenges in exercises performed against gravity (eg, squat or bench press) is to obtain accurate measurements of v_0 because of the large extrapolation needed from the experimental points to the velocity-axis.[6] This problem could be minimized by modeling the load-velocity (L-V) relationship (external load lifted expressed in kg vs lifting velocity) instead of the F-V relationship (force production expressed in N vs lifting velocity). Therefore, it seems important to explore the potential use of the variables derived from the L-V relationship as a substitute for standard tests commonly used to evaluate maximal neuromuscular capacities.

The relationship between the external load lifted and movement velocity can be modeled by a simple linear regression that yields the slope of the L-V relationship, the load-axis intercept (ie, load at zero velocity; L_0), and v_0 (ie, velocity at zero load).[12,15] The changes in these 3 variables have been recently used to compare the effects of 2 resistance training programs differing in the set configuration on neuromuscular performance.[12] However, in the scientific literature, a more often used procedure to evaluate changes in neuromuscular performance before and after a training intervention consists of comparing the velocity achieved with the same absolute loads[21,24] or the average velocity attained with light (eg, >1.0 $m \cdot s^{-1}$) and heavy (eg, <1.0 $m \cdot s^{-1}$) loads.[21] In this regard, the assessment of L_0 and v_0 through the L-V relationship could provide a simpler, less arbitrary, and more comprehensive indicator of the individual's capacity to apply force at low and high velocities, respectively. A third variable that can be derived from the combination of L_0 and v_0 is the area under the line of the L-V relationship ($A_{line} = L_0 \cdot v_0/2$). Since A_{line} essentially represents a combination of L_0 and v_0, it is plausible that this variable could serve as an indicator of the maximal power capacity of an individual. However, to our knowledge, no study has examined the feasibility of the variables derived from the L-V relationship (L_0, v_0, and A_{line}) as indicators of the maximal capacities of an individual to produce force, velocity, and power.

To address the existing gaps in the literature, the first aim of this study was to evaluate the between-session reliability of the variables derived from the L-V relationship (L_0, v_0, and A_{line}) during the concentric-only and eccentric-concentric back-squat variants. The second aim of the study was to explore the concurrent validity of L_0 and A_{line} with regard to traditional tests commonly used to evaluate the maximal capacities of the muscles to produce force and power, respectively. Therefore, we hypothesized that the L-V relationship variables will be highly reliable and that they would be highly associated with the traditional tests commonly used to evaluate the maximal mechanical capacities of the muscles to produce force and power.

METHOD

Participants

Twenty-four male wrestlers volunteered to participate in this study (age = 19.1 ± 3.4 years, body height = 1.72 ± 0.06 m; body mass = 74.1 ± 11.9 kg; back-squat 1RM = 132.3 ± 21.3 kg). All wrestlers were competing at the national level and were regularly performing the back-squat exercise in their training programs (4.8 ± 2.5 years). Participants were not allowed to perform any strenuous physical activity during the 24 hours preceding each testing session. Before commencement of the study, participants were informed about the study procedures, and they or their legal guardians (for participants <18 years) gave written consent to participate in the study. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the institutional review board (IRB approval: 687/CEIH/2018).

Study Design

A repeated-measures design was used to explore the between-session reliability and concurrent validity of the L-V relationship variables (L_0, v_0, and A_{line}) during 2 variants of the back-squat exercise. After a preliminary 1RM testing session, participants undertook 4 experimental sessions over 2 consecutive weeks. In a counterbalanced order, participants performed 2 consecutive sessions using the concentric-only back-squat variant, and then 2 sessions using the eccentric-concentric back-squat variant (Figure 1). Consecutive testing sessions were separated by at least 48 hours of rest. For each back-squat variant, the data from both sessions were used to address the first objective (between-session reliability), but only the data from the first session were used to address the second objective (concurrent validity). All testing sessions were performed in a Smith machine (Technogym) and were conducted at the same time of day for each participant (±1 hour) and under similar environmental conditions (~22°C and ~60% humidity).

Procedures

In a preliminary session, participants' body height and body mass (Seca model 654, Seca) were measured. Thereafter, they performed a standardized warm-up, which consisted of running on a treadmill for 10 minutes at 6.5 $km \cdot h^{-1}$, dynamic stretching, and 1 set of 5 repetitions with an external load of 17 kg (mass

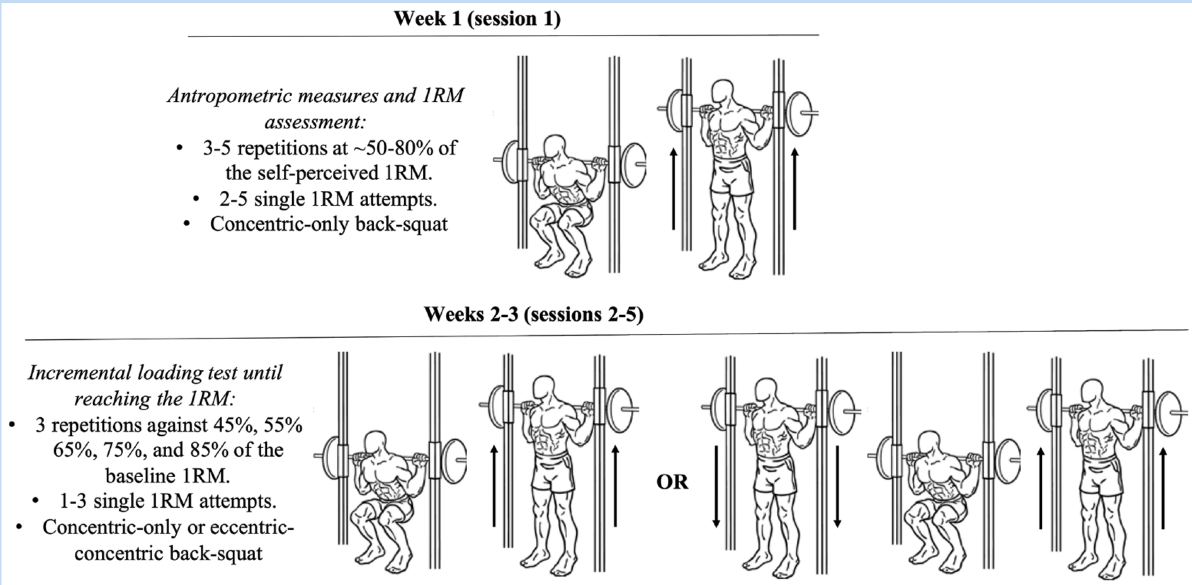

Figure 1. Overview of the experimental design. 1RM, 1-repetition maximum.

of the unloaded Smith machine barbell). Afterward, the 1RM testing protocol (3-5 repetitions at ~50%-80% of perceived 1RM, followed by 2-5 single 1RM attempts) was performed to determine participants' baseline 1RM in the concentric-only back-squat variant. Three minutes of rest was given between sets and 1RM attempts. The baseline 1RM was determined so that more accurate relative intensities from 1RM could be lifted in the experimental sessions.

Each experimental session started with the same warm-up described earlier. After a brief rest, participants performed an incremental loading test until reaching the 1RM during the back-squat exercise using either the concentric-only or eccentric-concentric variants. The incremental loading test consisted of performing 3 repetitions against 5 relative loads (45%, 55%, 65%, 75%, and 85% on the baseline 1RM determined in the preliminary session), followed by 1 to 3 1RM attempts. The load increment during 1RM attempts was decided based on mutual consensus between the participant and the experienced researcher. Interrepetition rest was set at 10 seconds and interset rest was fixed at 3 minutes for submaximal loads and 5 minutes for 1RM attempts. Velocity feedback was verbally provided immediately after completing each repetition to encourage participants to perform all repetitions at maximal intended velocity. Two spotters were standing on each side of the barbell to ensure safety. The specific characteristics of the 2 back-squat variants are provided next.

Concentric-Only Back-Squat Variant

Participants initiated the movement from a fully extended position with the feet shoulder-width apart and the barbell held across the back at the level of the acromion ("high-bar position"). From this position, they were instructed to descend in a continuous manner until reaching 90° of knee flexion, hold this position for ~2 seconds, and then return to the initial position as fast as possible. The squat depth was individually controlled using an elastic cord positioned under participants' hips. Participants were also instructed to keep constant downward pressure on the barbell throughout the whole movement, and they were not allowed to jump off the ground.

Eccentric-Concentric Back-Squat Variant

The execution technique was identical to the concentric-only back-squat variant except that participants initiated the lifting phase immediately after reaching 90° of knee flexion (ie, there was no pause between the lowering and lifting phases).

Data Acquisition and Analysis

A validated linear position transducer (GymAware PowerTool, Kinetic Performance Technologies) was used to record the mean values of velocity and power of all repetitions.[31] The tether of the linear position transducer was attached to the barbell using a Velcro strap. Velocity and acceleration data were calculated from the first and second derivatives of the change in barbell position with regard to time, while force data were calculated by multiplying the external load lifted by the total acceleration (gravity + acceleration of the barbell). Finally, power was computed as the product of force and velocity. Data obtained from the device were transmitted via Bluetooth to a tablet (iPad, Apple Inc) using the GymAware v2.8 app, and to the online cloud before being exported to Microsoft Excel (Microsoft Corporation) and prepared for further analysis.

The L-V and power-velocity (P-V) relationships were calculated from the individual values of velocity and power collected under all loading conditions. A least-square linear

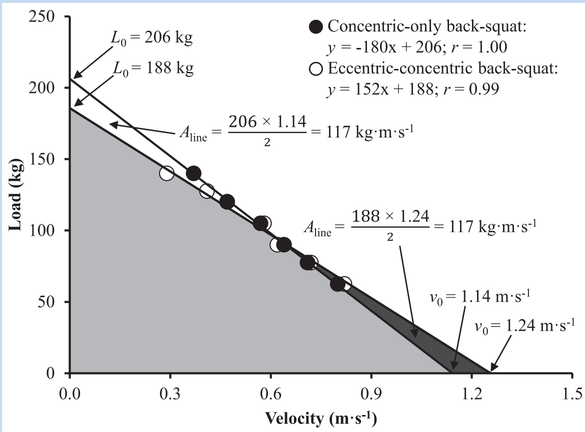

Figure 2. Representation of the 3 load-velocity relationship variables obtained by a representative participant during the back-squat exercise performed using the concentric-only (black circles) and eccentric-concentric (white circles) variants. The regression equation and Pearson's product-moment correlation coefficient (r) are depicted. A_{line}, area under the load-velocity relationship line; L_0, load-axis intercept; v_0, velocity-axis intercept.

regression model ($L[V] = L_0 - sV$) was used to determine the L-V relationships, where L_0 represents the load at zero velocity and s is the slope of the L-V relationship.[12] The maximal velocity capacity (v_0) and the area under the L-V relationship line (A_{line}) were then calculated as follows: $v_0 = L_0/s$ and $A_{line} = L_0 \cdot v_0/2$ (see Figure 2 for further details). The highest (best) velocity as well as the average velocity of the 3 repetitions performed at each load were used for modeling the L-V relationships to examine whether selection of the repetitions affects the reliability of the L-V relationship parameters. The P-V relationships were obtained after applying a second-order polynomial regression model, where the apex corresponds to the maximum power (ie, P_{max}).[23] Only the repetition with the highest velocity obtained at each load was used for modeling the P-V relationships. Therefore, 5 dependent variables were considered in the present study: L_0, v_0, and A_{line} derived from the L-V relationship as well as 1RM and P_{max} commonly used to evaluate maximal force and power capacities, respectively.

Statistical Analyses

Descriptive data are presented as mean, SD, and range. The normal distribution of the data was confirmed by the Shapiro-Wilk test ($P > 0.05$). The strength of the L-V and P-V relationships was examined through the Pearson's product-moment correlation coefficient (r). Paired samples t-tests and Cohen's d effect size (ES) were used to compare the magnitude of the differences between the variables derived from the L-V relationship (L_0, v_0, and A_{line}) from both testing sessions. The magnitude of the ES was interpreted as follows: trivial (<0.20), small (0.20-0.59), moderate (0.60-1.19), large (1.20-2.00), and very large (>2.00).[9] Between-session reliability was assessed by the coefficient of variation (CV% = standard error of measurement/participants' mean score × 100) and the intraclass correlation coefficient (ICC; model 3.1) with their corresponding 95% confidence intervals. The following criteria were used to determine acceptable (CV ≤ 10%, ICC ≥ 0.80) and high (CV ≤ 5%, ICC ≥ 0.90) reliability.[23] The ratio between 2 CVs was used to compare the reliability between the 2 back-squat variants (concentric-only and eccentric-concentric) and 2 repetition criteria (best and average). The smallest important ratio between 2 CVs was considered to be higher than 1.15.[23] Finally, the r coefficient was used to explore the concurrent validity of L_0 and A_{line} with regard to 1RM and P_{max}, respectively. The criteria used to interpret the magnitude of the r coefficients were the following: trivial (0.00-0.09), small (0.10-0.29), moderate (0.30-0.49), large (0.50-0.69), very large (0.70-0.89), nearly perfect (0.90-0.99), and perfect (1.00).[9] All reliability assessments were performed by means of a custom Microsoft Excel spreadsheet,[9] while other statistical analyses were performed using the statistical software (SPSS Version 22.0, IBM Corp). Alpha was set at 0.05.

RESULTS

The strength of the L-V (r range = 0.90-1.00) and P-V (r range = 0.80-0.99) relationships ranged from very large to perfect during both variants of the back-squat exercise. Nonsignificant ($P \geq 0.23$) and trivial (ES ≤ 0.07) differences were observed for L_0, v_0 and A_{line} between both testing sessions. The between-session reliability was high for the A_{line} (CV range = 2.58%-4.37%; ICC range = 0.98-0.99) and generally acceptable for L_0 (CV range = 5.25%-9.01%; ICC range = 0.77-0.91) and v_0 (CV range = 5.08%-8.66%; ICC range = 0.45-0.72) (Table 1). Whether the highest or the average velocity of the 3 repetitions was included in the model did not meaningfully affect the reliability of the L-V relationship variables in 4 of 6 comparisons (CV_{ratio} range = 1.03-1.13). However, the reliability was higher when the highest velocity was taken in the model in 2 of 6 comparisons compared with the average velocity (CV_{ratio} range = 1.15-1.37). The L-V relationship variables were always more reliable during the concentric-only back-squat variant compared with the eccentric-concentric back-squat variant (CV_{ratio} range = 1.49-1.65) (Figure 3).

Very large correlations were observed between L_0 and the 1RM strength (r_{range} = 0.87-0.88; $P < 0.001$), while nearly perfect correlations were found between the A_{line} and P_{max} (r = 0.98-0.99; $P < 0.001$) (Figure 4).

DISCUSSION

This study was designed to evaluate the between-session reliability and concurrent validity of the L-V relationship variables (L_0, v_0, and A_{line}) obtained during 2 variants of the back-squat exercise. Supporting our first hypothesis, the L-V relationship variables were generally obtained with a high (A_{line}) or acceptable (L_0 and v_0) between-session reliability. Our second

Table 1. Reliability of the variables derived from the load-velocity (L-V) relationship using the best and average scores of mean velocity during the back-squat exercise performed using the concentric-only and eccentric-concentric variants

L-V Relationship Variables	Repetition Criterion	Back-Squat Variant	Session 1 (Mean ± SD)	Session 2 (Mean ± SD)	*P*	ES	CV, % (95% CI)	ICC (95% CI)[a]
L_0 (kg)	Best score	Concentric-only	185 ± 30	186 ± 34	0.72	0.03	5.25 (4.08, 7.36)	0.91 (0.81, 0.96)
		Eccentric-concentric	181 ± 34	182 ± 29	0.73	0.05	7.82 (6.07, 10.96)	0.81 (0.61, 0.91)
	Average score	Concentric-only	189 ± 29	190 ± 34	0.79	0.03	5.47 (4.25, 7.67)	0.90 (0.78, 0.96)
		Eccentric-concentric	184 ± 36	185 ± 30	0.96	0.01	9.01 (7.00, 12.64)	**0.77 (0.53, 0.89)**
v_0 (m·s^{-1})	Best score	Concentric-only	1.14 ± 0.12	1.14 ± 0.09	0.68	–0.07	5.08 (3.95, 7.13)	**0.71 (0.44, 0.87)**
		Eccentric-concentric	1.21 ± 0.15	1.21 ± 0.11	0.98	0.01	7.69 (5.98, 10.79)	**0.52 (0.16, 0.76)**
	Average score	Concentric-only	1.08 ± 0.12	1.08 ± 0.10	0.89	–0.02	5.51 (4.28, 7.73)	**0.72 (0.45, 0.87)**
		Eccentric-concentric	1.15 ± 0.15	1.16 ± 0.11	0.74	0.07	8.66 (6.73, 12.14)	**0.45 (0.07, 0.72)**
A_{line} (kg·m·s^{-1})	Best score	Concentric-only	106 ± 23	106 ± 22	0.77	–0.01	2.58 (2.01, 3.62)	0.99 (0.97, 0.99)
		Eccentric-concentric	109 ± 26	111 ± 24	0.34	0.05	4.26 (3.31, 5.98)	0.97 (0.93, 0.99)
	Average score	Concentric-only	103 ± 22	102 ± 21	0.85	–0.01	3.53 (2.74, 4.95)	0.98 (0.94, 0.99)
		Eccentric-concentric	106 ± 25	107 ± 23	0.23	0.07	4.37 (3.40, 6.14)	0.97 (0.93, 0.99)

A_{line}, area under the L-V relationship line; CV, coefficient of variation; ES, Cohen's *d* effect size ([session 2 – session 1]/SD both); ICC, intraclass correlation coefficient; L_0, load-axis intercept; *P*, *P*-value obtained through a paired-samples *t*-tests between sessions 1 and 2; v_0, velocity-axis intercept.

[a]Boldfaced numbers indicate an unacceptable reliability (CV > 10%, or ICC < 0.80).

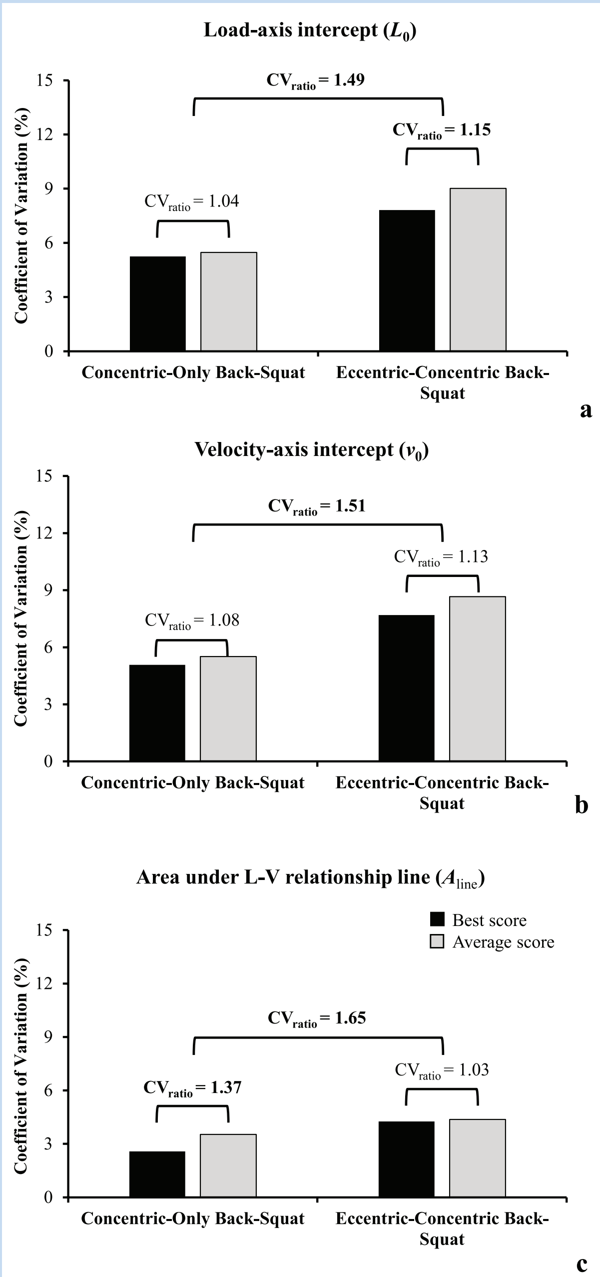

Figure 3. Reliability comparisons between the best (back bars) and average (white bars) scores and between the concentric-only and eccentric-concentric back-squat variants for the load-axis intercept (A), velocity-axis intercept (B), and area under the load-velocity (L-V) relationship line (C). Numbers depict the ratio between 2 coefficients of variation (CV_{ratio} = higher value/lower value), while meaningful differences in reliability ($CV_{ratio} > 1.15$) are indicated in boldface. The 2 back-squat variants were compared considering the best score as this criterion provided a comparable or higher reliability than the average score.

hypothesis was also confirmed since the L-V relationship variables reported very large (L_0 vs 1RM strength) and nearly perfect (A_{line} vs P_{max}) correlations with respect to the traditional tests commonly used to evaluate the maximal mechanical capacities of the muscles to produce force and power, respectively. Collectively, these results highlight that the L-V relationship is a reliable and valid procedure, which allows for a quick and simple assessment of the maximal capacities of the neuromuscular system to produce force, velocity, and power.

An indispensable asset of any physical test is the reliability of the measurement.[9] The results of the present study indicate that the between-session reliability was high for A_{line} and acceptable for L_0 and v_0 during the 2 variants of the back-squat exercise. These reliability outcomes are remarkably better than those demonstrated by Iglesias-Soler et al[11] for the F-V relationship parameters obtained during the eccentric-concentric back-squat variant: F_0 (CV = 5%; ICC = 0.93), v_0 (CV = 14%; ICC = 0.72), and P_{max} (CV = 11%; ICC = 0.85). The lower reliability of the F-V relationship parameters observed by Iglesias-Soler et al[11] could be explained by the greater manipulation of the velocity-time data to obtain force values and the higher extrapolation from the experimental points to v_0.[6] This latter argument might be supported by the findings of the present study since trivial differences in reliability were observed between L_0 and v_0, whereas studies[3,6,11] examining the reliability of the F-V relationship parameters during exercises performed against gravity (eg, vertical jumps and bench press) typically observed v_0 with lower reliability than F_0. Therefore, the L-V relationship variables present 2 important advantages in comparison with the F-V relationship parameters: (1) they can be obtained with a higher reliability (especially v_0) and (2) an estimation of force outputs is not necessary because only velocity outputs need to be recorded. However, it is worth noting that L-V relationship variables do not present a clear physiological meaning unlike the maximal mechanical capacities of the muscles to produce force, velocity, and power that can be determined through the modeling of the F-V relationship.[13]

The determination of the individualized L-V relationship requires the assessment of the velocity at which 2 or more loads are lifted.[22] It is common that multiple (2-4) repetitions are performed with the same load, and later it should be decided whether the best (ie, highest) or the average velocity of the multiple repetitions will be used for modeling the L-V relationships.[7,10,25,30] However, there is still no scientific consensus on the most appropriate approach (best vs average score) for the modeling the L-V relationship.[4,26] Our findings show that the L-V relationship variables generally reported a comparable between-session reliability for both approaches (4 of 6 comparisons), but in 2 of 6 comparisons (L_0 during the eccentric-concentric squat, and P_{max} during the concentric-only squat), the reliability was higher when the highest velocity was used for modeling purposes. These results are in line with the findings of Pérez-Castilla et al[22] who found that the accuracy of the predicted 1RM was not affected by whether the single highest repetition or the average velocity of the multiple

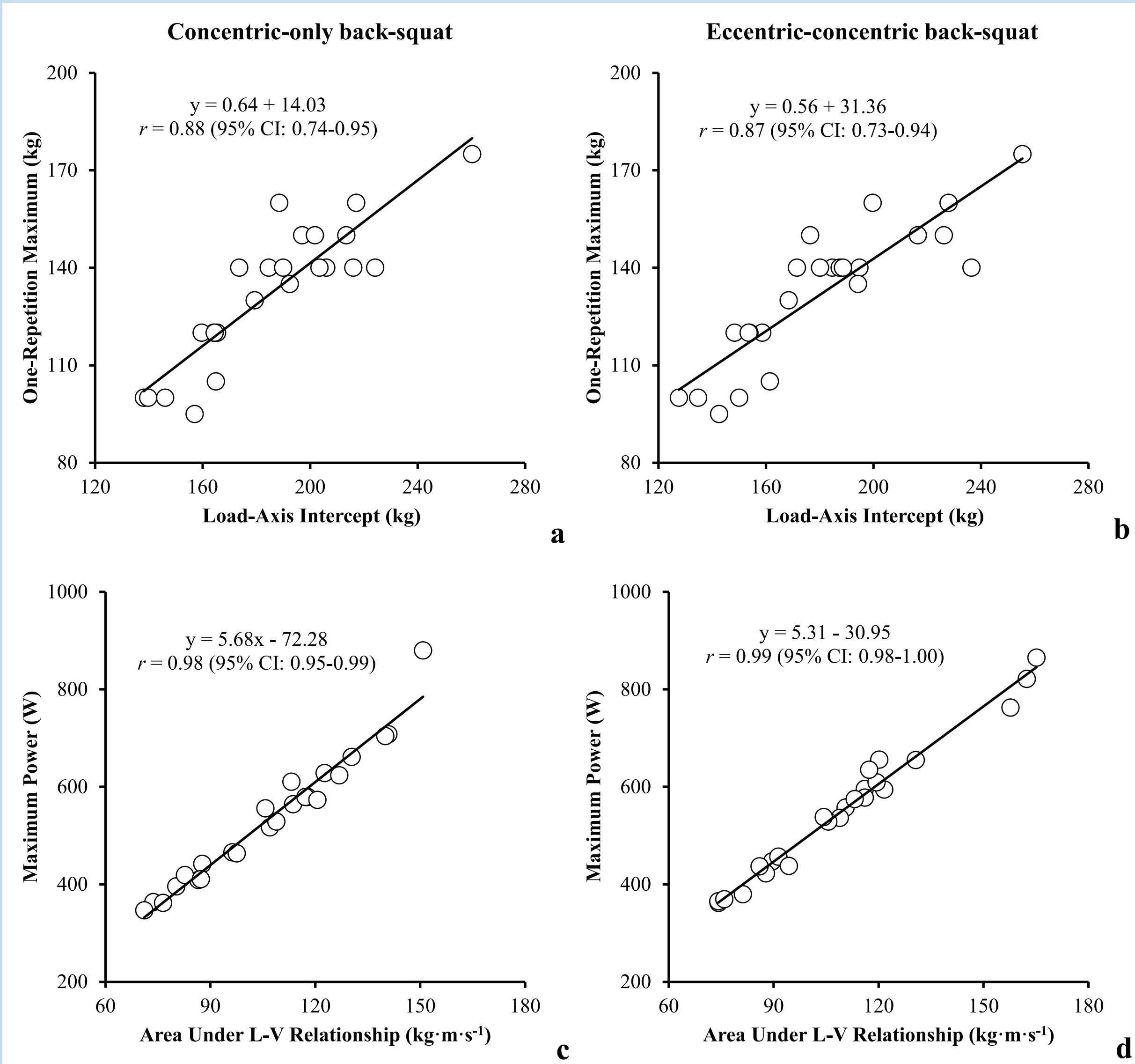

Figure 4. Relationship of the variables derived from the load-velocity (L-V) relationship with the traditional tests commonly used to evaluate maximal force (load-axis intercept vs 1-repetition maximum; A and B) and power (area under the L-V relationship line vs maximum power; C and D) capacities during the back-squat exercise performed using the concentric-only (A and C) and eccentric-concentric (B and D) variants. Regression equations and Pearson's correlation coefficients (*r*) with their corresponding 95% confidence intervals (CI) are depicted.

repetitions were used for establishing an individual L-V profile during the free-weight bench press exercise. The similarity between the results of the present study and that by Pérez-Castilla et al[22] is probably caused by the low within-subject variability observed for the velocity outputs achieved against the multiple repetitions performed with the same absolute load (CV ≤ 7.2% and 6.6%, respectively). Hence, in lieu of the available evidence, it is plausible that variables obtained with a high reliability are not affected by whether the highest (ie, the best) or the average velocity of the repetitions are used for modeling purposes. The best repetition could be the preferred option because it is expected to more closely represent the maximum performance of an individual. However, when the velocity outputs are obtained with a greater within-subjects variability (ie, lower reliability), average velocity of the repetitions might then be preferable instead.[26]

The back-squat is one of the exercises often used in the scientific literature to explore the characteristics of the L-V relationship.[16,17,20,25] Previous research has examined the influence of the stretch-shortening cycle,[20,25] squat depth,[17] and bar position[16] on the L-V relationship. Furthermore, from a reliability standpoint, it has been shown that the concentric-only back-squat variant provides more reliable velocity measurements across a wide range of relative loads (30%-100%1RM) than the eccentric-concentric back-squat variant (CV: 2.9% vs 4.1%).[20] In accordance with the study from Pallarés et al,[20] our results suggest that the 3 variables derived from the L-V relationship were always obtained with a greater reliability using the concentric-only back-squat variant compared with the eccentric-concentric back-squat variant. Importantly, these findings were similar despite that the instructions regarding the execution of the lowering phase during the eccentric-concentric back-squat variant differed between studies. More specifically, in the present study, participants were instructed to perform the lowering phase at a self-selected fast velocity, while in the study by Pallarés et al,[20] participants performed the lowering phase in a controlled manner guided by a metronome. Based on these results, the concentric-only back-squat variant could be recommended to obtain the L-V relationship variables with a greater reproducibility.

A pioneering study conducted by Jidovtseff et al[14] reported a high association between L_0 and the 1RM in the bench press exercise ($r \geq 0.96$). Therefore, it is not surprising that other research showed how the L_0, obtained by modeling the individual L-V relationship, allows for accurate estimations of the 1RM in other resistance training exercises such as prone row, overhead press, and the back-squat.[10] In line with the previous findings from Jidovtseff et al,[14] our findings confirm the high concurrent validity of L_0 with regard to the 1RM during the 2 variants of the back-squat exercise. These results are also in agreement with previous studies[2,27] that revealed moderate-to-large correlations between the F_0 obtained during squat jump and the back-squat 1RM. Furthermore, our results demonstrate for the first time that the A_{line} is nearly perfectly correlated with P_{max}. This information is of utmost importance since A_{line} could provide an indicator of the overall mechanical performance similar to the maximal power capacity that can be obtained by modeling the F-V relationship. Collectively, the present study adds evidence suggesting that the L-V relationship variables reported very large (L_0) and nearly perfect (A_{line}) correlations with regard to the standard tests commonly used to evaluate the maximal mechanical capacities of the muscles to produce force and power, respectively. Therefore, the L-V relationship variables could be used as substitutes of traditional measures of maximal strength (1RM) and power (P_{max}).

Finally, several limitations of the present study need to be recognized. First, since athletes typically perform the back-squat exercise with free-weights, the use of a Smith machine—which restricts the movement of the barbell to the vertical direction—may limit the ecological validity of our findings. However, it should be noted that machine-based exercises provide more reliable measures of movement velocity than free-weight exercises.[18] Similarly, since the reliability and concurrent validity of the F-V relationship parameters seem to be exercise specific,[2,3,11] the generalizability of our findings to other resistance training exercises may be limited. In this regard, future studies should examine the feasibility of the L-V relationship variables to evaluate the maximal capacities in the free-weight back-squat variants and other multi-joint tasks (eg, jumps or pulling exercises). Second, the concurrent validity of v_0 should be examined with regard to standard tests not performed against gravity (eg, horizontal squat jumps).[28] Finally, since lifting very heavy loads and performing repetitions against multiple loads is not always logistically possible during routine testing procedures, future studies should examine the optimal combination of loads that allows for accurate determination of the L-V relationship variables with minimal time and effort.

CONCLUSION

The variables derived from the L-V relationship can be obtained with a high (A_{line}) or acceptable (L_0 and v_0) between-session reliability, and with a high concurrent validity (L_0 and A_{line}) during the back-squat exercise performed using the concentric-only and eccentric-concentric variants. Although the outcomes of the L-V relationship may not present clear physiological meaning unlike the F-V relationship parameters, the assessment of the L-V relationship represents a quick, simple, and precise procedure to estimate the maximal force (L_0), velocity (v_0), and power (A_{line}) capacities of the lower-body muscles for 2 main reasons: (1) force output does not need to be computed for modeling the relationships and (2) the extrapolation needed from the experimental points to v_0 is reduced. Additionally, our findings revealed that whether the highest (ie, the best repetition) or the average velocity of the repetitions was used for modeling L-V relationship did not present a meaningful effect on the reliability of the L-V relationship parameters. However, the best repetition could still be a preferred option because it is expected to more closely represent the maximum performance of an individual. Finally, the concentric-only back-squat variant could be recommended for modeling the L-V relationship since the 3 L-V relationship parameters were obtained with a greater reliability compared with using the eccentric-concentric back-squat variant.

REFERENCES

1. Cormie P, Mccaulley GO, Triplett NT, Mcbride JM. Optimal loading for maximal power output during lower-body resistance exercises. *Med Sci Sports Exerc*. 2007;39:340-349.
2. Cuk I, Markovic M, Nedeljkovic A, Ugarkovic D, Kukolj M, Jaric S. Force-velocity relationship of leg extensors obtained from loaded and unloaded vertical jumps. *Eur J Appl Physiol*. 2014;114:1703-1714.
3. Feeney D, Stanhope SJ, Kaminski TW, Machi A, Jaric S. Loaded vertical jumping: force-velocity relationship, work, and power. *J Appl Biomech*. 2016;32:120-127.
4. Garcia-Ramos A, Jaric S, García-Ramos A, Jaric S. Two-point method: a quick and fatigue-free procedure for assessment of muscle mechanical capacities and the one-repetition maximum. *Strength Cond J*. 2018;40:54-66.
5. García-Ramos A, Jaric S, Padial P, Feriche B. Force-velocity relationship of upper body muscles: traditional versus ballistic bench press. *J Appl Biomech*. 2016;32:178-185.
6. García-Ramos A, Pérez-Castilla A, Jaric S. Optimisation of applied loads when using the two-point method for assessing the force-velocity relationship during vertical jumps. *Sports Biomech*. 2018;20:274-289.
7. García-Ramos A, Suzovic D, Pérez-Castilla A. The load-velocity profiles of three upper-body pushing exercises in men and women. *Sports Biomech*. 2021;20:693-705.
8. Haff GG, Nimphius S. Training principles for power. *Strength Cond J*. 2012;34:2-12.

9. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci in Sports Exerc*. 2009;41:3-12.
10. Hughes LJ, Peiffer JJ, Scott BR. Load-velocity relationship 1RM predictions: a comparison of Smith machine and free-weight exercise. *J Sports Sci*. 2020;38:2562-2568.
11. Iglesias-Soler E, Mayo X, Rial-Vázquez J, et al. Reliability of force-velocity parameters obtained from linear and curvilinear regressions for the bench press and squat exercises. *J Sports Sci*. 2019;37:2596-2603.
12. Iglesias-Soler E, Rial-Vázquez J, Boullosa D, et al. Load-velocity profiles change after training programs with different set configurations. *Int J Sports Med*. 2021;42:794-802.
13. Jaric S. Force-velocity relationship of muscles performing multi-joint maximum performance tasks. *Int J Sports Med*. 2015;36:699-704.
14. Jidovtseff B, Harris NK, Crielaard JM, Cronin JB. Using the load-velocity relationship for 1RM prediction. *J Strength Cond Res*. 2011;25:267-270.
15. Jovanovic M, Flanagan EP. Researched applications of velocity based strength training. *J Aust Strength Cond*. 2014;22:58-69.
16. Kasovic J, Martin B, Fahs CA. Kinematic differences between the front and back squat and conventional and sumo deadlift. *J Strength Cond Res*. 2019;33:3213-3219.
17. Martínez-Cava A, Morán-Navarro R, Sánchez-Medina L, González-Badillo JJ, Pallarés JG. Velocity- and power-load relationships in the half, parallel and full back squat. *J Sports Sci*. 2019;37:1088-1096.
18. Miller RM, Freitas EDS, Heishman AD, et al. Test-retest reliability between free weight and machine-based movement velocities. *J Strength Cond Res*. 2020;34:440-444.
19. Niewiadomski W, Laskowska D, Gąsiorowska A, Cybulski G, Strasz A, Langfort J. Determination and prediction of one repetition maximum (1RM): safety considerations. *J Hum Kinet*. 2008;19:109-120.
20. Pallarés JG, Sánchez-Medina L, Pérez CE, De La Cruz-Sánchez E, Mora-Rodriguez R. Imposing a pause between the eccentric and concentric phases increases the reliability of isoinertial strength assessments. *J Sports Sci*. 2014;32:1165-1175.
21. Pareja-Blanco F, Rodríguez-Rosell D, Sánchez-Medina L, et al. Effects of velocity loss during resistance training on athletic performance, strength gains and muscle adaptations. *Scand J Med Sci Sports*. 2017;27:724-735.
22. Pérez-Castilla A, Fernandes JFT, García-Ramos A. Validity of the bench press one-repetition maximum test predicted through individualized load-velocity relationship using different repetition criteria and minimal velocity thresholds. *Isokinet Exerc Sci*. 2021;29:369-377.
23. Pérez-Castilla A, García-Ramos A. Force-velocity vs. power-velocity relationships: which method provides the maximum power and optimal velocity with higher reliability during the leg cycle-ergometer and bench press throw exercises? *Meas Phys Educ Exerc Sci*. 2021;25:294-305.
24. Pérez-Castilla A, Garcia-Ramos A, Padial P, et al. Effect of different velocity loss thresholds during a power-oriented resistance training program on the mechanical capacities of lower-body muscles. *J Sports Sci*. 2018;36:1331-1339.
25. Pérez-Castilla A, García-Ramos A, Padial P, Morales-Artacho AJ, Feriche B. Load-velocity relationship in variations of the half-squat exercise. *J Strength Cond Res*. 2020;34:1024-1031.
26. Picerno P. Good practice rules for the assessment of the force-velocity relationship in isoinertial resistance exercises. *Asian J Sports Med*. 2017;8:e15590.
27. Riviere JR, Rossi J, Jimenez-Reyes P, Morin J-B, Samozino P. Where does the one-repetition maximum exist on the force-velocity relationship in squat? *Int J Sports Med*. 2017;38:1035-1043.
28. Samozino P, Rivière JR, Rossi J, Morin J-B, Jimenez-Reyes P. How fast is a horizontal squat jump? *Int J Sports Physiol Perform*. 2018;13:910-916.
29. Suchomel TJ, Nimphius S, Stone MH. The importance of muscular strength in athletic performance. *Sports Med*. 2016;46:1419-1449.
30. Torrejón A, Balsalobre-Fernández C, Haff GG, García-Ramos A. The load-velocity profile differs more between men and women than between individuals with different strength levels. *Sports Biomech*. 2019;18:245-255.
31. Weakley J, Morrison M, García-Ramos A, Johnston R, James L, Cole MH. The validity and reliability of commercially available resistance training monitoring devices: a systematic review. *Sports Med*. 2021;51:443-502.