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RESEARCH

Impact of the optimal minimum velocity threshold on the accuracy of one repetition maximum estimation-based on a mixed model

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Abstract

Purpose This study aimed at developing two mixed methods approaches for 1RM prediction (generalized equations together with the individual load–velocity relationship—LVR). The validity of such equations was explored and compared with the validity of individual LVRs.

Methods The submaximal LVRs of seventy-six males was obtained for the free-weight back squat. Theoretical load at zero velocity (LD0), the slope of the individual LVR, and the individual ($Model_{IND}$) and optimal minimum velocity thresholds (MVT) ($Model_{OPT}$) were selected to develop the equations. Prediction accuracy was determined through mean differences, absolute percent errors and Bland–Altman plots.

Results $Model_{IND}$ was predictive of 1RM ($p < 0.0001$), explaining 89.7% of its variance. $Model_{OPT}$ increased the prediction power of 1RM to 98.7% ($p < 0.0001$). No significant differences in the absolute percent errors were found (4.7 and 3.9%, for $Model_{IND}$ and $Model_{OPT}$, respectively). The mean difference between actual and estimated 1RM was nearly zero for both models, while individual LVRs relying on the individual MVT displayed the contrary. The limits of agreement were 15.1 and 11.4 kg for $Model_{IND}$ and $Model_{OPT}$, respectively.

Conclusion The individual and optimal MVTs add predictive value to LD0 and the slope of the individual LVR for 1RM estimation on a group level and avoid error trends over the entire muscular strength spectrum. However, only $Model_{IND}$ increased the accuracy of estimations when compared with the more direct approach. From a practical standpoint, practitioners are encouraged to rely on the individual LVR instead of $Model_{OPT,}$ when using the optimal MVT for estimation purposes.

Keywords Maximum strength · Resistance training · Velocity-based training

Introduction

One-repetition maximum (1RM) is frequently used for testing maximum dynamic strength and is highly relevant for prescribing resistance training intensity [1]. Despite its high validity and reliability, the direct determination of 1RM is not without a few limitations [2]. For instance, it may be impractical for testing large groups of athletes and it may cause undue fatigue [3]. To counter the obstacles inherent to this methodology, indirect predictive approaches based on the movement velocity have more recently gained popularity [4–6]. There is general agreement that the concentric movement velocity and the magnitude of the load lifted display a negative linear relationship, at least in response to multi-joint resistance exercises (coefficient of determination > 0.9) [7]. Because of this, it has been proposed that estimations of 1RM might be

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possible by extrapolation based on the load–velocity relationship (LVR) [5, 6, 8–10].

Several generalized equations (fixed equation which disregard individual differences) have even been developed for this particular purpose [11–13]. Yet, the ad hoc use of generalized equations for estimating 1RM is problematic because the LVR is affected by several factors that preclude valid predictions based on this approach (e.g. exercise selection, execution technique, sex and individual strength levels) [14, 15]. As such, the individual LVR (equation which accounts for individual neuromuscular capacities) is preferable for estimating 1RM as well as for monitoring training loads on a session-by-session basis [16]. By measuring the mean concentric velocity (MCV) at 1RM (minimum velocity threshold—MVT) and entering its value in the individual LVR regression equation, it is possible to estimate 1RM [17]. However, the individual MVT shows high within-subject variability [6, 17]. This means that, to ensure an acceptable accuracy of the estimation, the pre-determination of the 1RM would be required on a regular basis [6, 17]—affecting the feasibility and practical relevance of this approach. In an attempt to solve these limitations, a mixed-model approach was recently tested for the estimation of the 1RM in response to the free-weight back squat [18]. This approach incorporates a generalized equation that takes into consideration two variables obtained via the individual LVR—the load at zero velocity (LD0—the *y* intercept of the relationship), and the slope of the LVR relationship [18]. It should be noted that both these variables can be obtained from a submaximal LVR and this is highly practical because the estimations can be computed without the a priori direct determination of 1RM. The model was shown to explain 84% of the variance of 1RM and the estimations had an absolute percent error of 6.9% [18].

It was also suggested that the inclusion of other particular variables within the model might increase its predictive capacity. For instance, a novel MVT variable was recently proposed in the literature—the optimal MVT. This MVT concept corresponds to the velocity that eliminates the differences between actual and predicted 1RM, and can be calculated as follows:

$$\text{Optimal MVT} = (\text{Actual 1RM} - \text{LD0})/\text{slope}. \quad (1)$$

To understand the optimal MVT concept, consider the following example: consider a hypothetical participant, with an actual 1RM of 150 kg, a slope of -144.55 kg/s.m^{-1} and a LD0 of 203.32 kg. In this scenario, it would be necessary to solve the individual load–velocity relationship linear equation for MCV to determine the value compatible with the actual 1RM (optimal MVT = [150 kg − 203.32 kg] / −144.55 kg/s.m^{-1} = 0.37 m.s^{-1}).

For instance, for the bench press, back squat and prone bench pull, the optimal MVT displayed higher predictive power than the individual MVT [19–21]. Thus, its inclusion in a mixed-model approach designed to predict 1RM on the free-weight back squat might add predictive value to such estimations. Despite losing its practicality (necessity of determining the 1RM to access the individual MVT and calculate the optimal MVT), by doing so, we can better understand how much the MVT variables contribute to improvements in estimation accuracy, even when individual characteristics are not controlled for, and address if the mixed-modelling approach surpasses the individual LVR in regard to 1RM estimation accuracy.

The aims of this study were threefold: (1) to examine if adding the individual or optimal MVT to a mixed-model approach improves the explained variance of 1RM in response to the free-weight back squat, and (2) to determine the validity of such models for 1RM prediction in this particular exercise, and (3) to compare the proposed mixed-models' 1RM estimations with the estimations derived from the individual LVRs.

Methods

Experimental approach to the problem

This study involved a repeated measures design consisting of 3 sessions structured to allow 1RM estimations (Fig. 1). A first session was performed for familiarization purposes. In the second and third sessions, a 1RM protocol took place and the individual LVRs were determined. All participants performed the second session, but only the data from a group of subjects was selected to compute the mixed models. Only the remaining subjects performed the third testing session with the goal of assessing the accuracy of the models. 1RM estimation accuracy between mixed models was assessed. Further, each model was compared with the individual LVR in regard to their accuracy to estimate the 1RM. Testing sessions were performed during the morning period, 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%. All subjects were tested in a postprandial state, approximately 2 h after their last meal.

Subjects

Seventy-six subjects were included in this study (age: 23.7 ± 4.5 years; height: 1.77 ± 0.07 m; body mass: 74.3 ± 10.5 kg). All subjects were young, healthy, male physical-education students. In addition, they were nonobese, nonsmokers, and free from any known diseases as assessed by a health-screening questionnaire, and free from

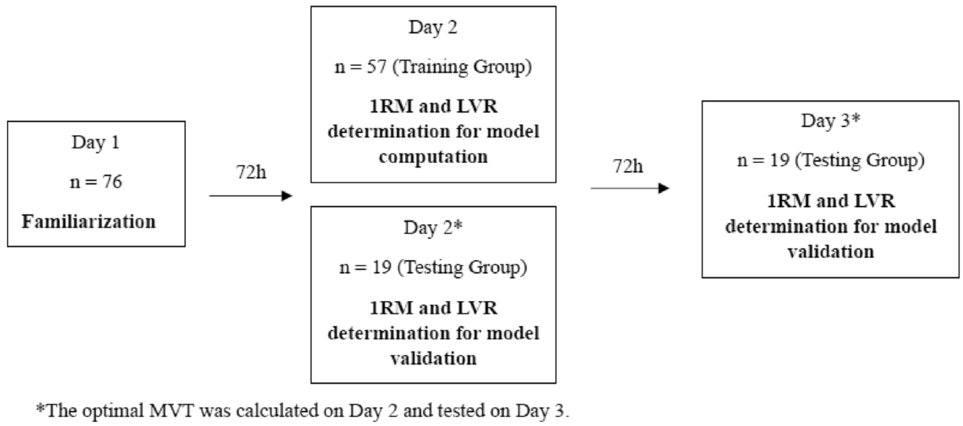

Fig. 1 Schematic of the experimental design. *1RM* one-repetition maximum, *LVR* load–velocity relationship, *MVT* minimum-velocity threshold

regular medication [22]. Moreover, all subjects were active, accumulating nine hours of physical activity per week as part of their academic work and they were all experienced in resistance training for at least two years, including the free-weight back squat (performed 2–3 times/week). To be included, each participant had to exhibit a free-weight back squat relative 1RM > 1.5 (absolute 1RM divided by body mass). Subjects attended two testing sessions with a duration of ~ 60 min. Written informed consent was obtained upon study entry. The experimental design complied with the principles set forth in the Declaration of Helsinki and was approved by the Faculty's Ethics Committee (CE*** Nº **/****).

Procedures

Subjects abstained from intense physical exercise for at least 24 h before each visit. Body mass (TANITA® BF-350, Arlington Heights, IL) and height (TANITA® HR-200, Arlington Heights, IL) were obtained during the first session, with the subjects wearing lightweight clothes and no shoes. Thereafter, for familiarization, all subjects performed 5 sets of 5 repetitions using a free-barbell (BOXPT®, Póvoa do Varzim, Portugal) (unloaded bar mass: 20 kg). Loading was increased on a set-by-set basis to enable familiarization with a wide range of loads. The subjects were asked to perform the concentric phase of each lift as fast as possible. On a second testing session (72 h after the first testing session), a protocol with progressive load increments was completed up to the actual 1RM (completion of a single maximal lift) [13]. The endpoint of each lift was defined as the full extension of both the knee and hip. All repetitions were performed at maximal intended concentric velocity, throughout the entire range of motion. Only 19 subjects performed a third testing session, which served the purpose of testing the validity of 1RM estimation based on the individual MVT and optimal MVT (both obtained during the previous session [pre-individual and pre-optimal MVT]) [19].

Load–velocity relationship

A warm-up consisting of 5 min of unloaded cycling (Monark Ergomedic 828E cycle ergometer, Monark Exercise AB, Vansbro, Sweden), followed by 3 sets of 10 callisthenic full squats preceded each test. Each participant then completed 3 sets of 5 repetitions with an unloaded bar (concentric phase performed as fast as possible). Squatting was performed with feet shoulder width apart and vertically aligned with the bar, while the bar rested on the upper trapezius.

Each lift started at a fully extended position. Then, the subjects descended at a natural speed (controlled manner) until touching their buttocks on a thin cord secured in the squat cage at a height that ensured that the thighs would be parallel to the floor. From this point, and without pausing, the concentric phase was performed as fast as possible until full extension of the hip and knee joint was attained. During all repetitions, the heels were allowed to lift off from the floor but jumping was not allowed. The load was progressively increased until 1RM was determined directly with the completion of a single successful maximal lift. All subjects 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) of 0.7 m.s^{-1} [23]. 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. All repetitions performed with a MCV < 0.35 m.s^{-1} were considered a 1RM attempt. For lighter (MCV > 1.15 m.s^{-1}), medium (0.7 < MCV < 1.15 m.s^{-1}) and heavy loads (MCV < 0.7 m.s^{-1}) the number of attempts varied from 3–5, 2–4 to 1–2, respectively. Velocity feedback was verbally provided after completing each repetition to encourage all subjects to perform all lifts at maximal intended velocity [24].

MCV was taken from the start of the concentric phase of each lift to the instant corresponding to the maximum height of the bar. Measurements were performed with a previously validated Chronojump linear position transducer, which sampled the bar's velocity at a frequency of 1000 Hz (Chronojump, Barcelona, Spain) [25]. The tether of the linear position transducer was attached to one extremity of the barbell using a Velcro strap and remained perpendicular to the ground during testing [18]. The recovery between sets was equivalent to 3 min and the duration of the resting period between repetitions in each set was < 5 s (only the best attempt for each load was recorded) [26]. LD0 and the slope of the LVR were extracted using a multipoint approach by plotting MCV in response to 4 back-squat loads (between 40 and 90%1RM) [27, 28]. Within this range of intensities, when plotting the LVRs, a careful selection of loads was performed to ensure that the individual velocity of the heaviest load would not differ from the individual MVT by more than 0.3 $m.s^{-1}$ and that the velocity of the lightest load would be 0.4 to 0.6 $m.s^{-1}$ faster than the one obtained for the heaviest load [29, 30]. Intermediate loads were selected by assuring they were as equidistant to the other experimental points, as possible. Subjects who performed all 3 sessions were tested on the same absolute loads on both sessions and these same loads were used to compute the LVRs.

Statistical analysis

Given that the regression analyses computed in this study involved less than 5 predictor variables, sample size was calculated based on the Harris's formula [31]. According to this formula, the number of subjects should exceed the number of predictors by at least 50 (number of predictors plus, at least, 50 subjects). Thus, to develop and cross-validate prediction models for 1RM, the final data set ($n = 76$) was divided into 75% "training" ($n = 57$) and 25% "testing" ($n = 19$) (Fig. 1). All data are presented as mean ± SD. The data were tested for normality with the Shapiro–Wilk test and for sphericity with the Mauchly's test.

Hierarchical multiple linear regression analysis was computed to determine whether LD0 (level 1), the slope (level 2) and the type of MVT (level 3) of the load–velocity profile (independent variables) were significant predictors of back-squat 1RM (dependent variable). The adjusted coefficient of determination (R^2) was used to determine the percent of variance explained by the regression model. The R^2 change was also determined to test the significance of adding the variable slope to LD0 on 1RM estimation. There was no concern regarding multicollinearity among predictor variables in multiple linear regression analysis (variance inflation factors < 1.6). The enter method was used to construct the mathematical prediction models. Both models were computed with the data of 57 subjects. The models were subsequently validated on the remaining 19 subjects using a hold-out cross validation. In specific, the multiple-regression equations derived from the "training group" were then used to estimate 1RM on all subjects included on the "testing group". A repeated measures ANOVA was performed to assess possible method effects (on the predicted 1RM values) [$Model_{IND}$ (mixed model, relying on the individual MVT) vs. $Model_{OPT}$ (mixed model, relying on the optimal MVT) vs. LVR_{IND} (individual LVR, relying on the individual MVT) vs. LVR_{OPT} (individual LVR, relying on the optimal MVT)]. Mean differences between actual and estimated 1RM were compared to zero using one-sided t tests. As a component of this method, we also determined the absolute percent error for the omitted participant, calculated as:

$$|(\text{actual}\,\%\,1\text{RM} - \text{estimated}\,\%\,1\text{RM}) \times 100/\text{actual}\,\%\,1\text{RM}|. \quad (2)$$

The following scale was used to characterize the magnitude of the absolute errors: low (< 5%), moderate (5–10%) and high (> 10%) [4]. The absolute percent errors of all methods were also compared using a repeated measures ANOVA. The agreement between actual and estimated %1RM for the "testing" subjects was analyzed with Bland–Altman plots. Bland–Altman plots were analyzed for heteroscedasticity. This was done by examining the significance of the Pearson's correlation coefficient between the absolute difference and mean values of each variable [32, 33]. Data analyses were performed using SPSS software version 27.0 (SPSS Inc., Armonk, NY, USA) and statistical significance was set a priori at $p < 0.05$.

Results

Subjects from both groups were of similar age and exhibited no significant differences in height or body mass (training: 23.2 ± 4.6 years, height: 1.77 ± 0.07 m, body mass: 74.1 ± 11.4 kg; testing: age: 25.0 ± 4.1 years, height: 1.76 ± 0.04 m, body mass: 74.9 ± 7.8 kg). Table 1 displays the data on the subjects' dynamic strength performance and LVR variables. The relative back-squat 1RM for this group of subjects was > 1.5, confirming their resistance-trained status. In addition, the mean number of 1RM attempts before failing a lift was 2. There was a strong linear relationship between load and velocity (minimum and maximum R^2 values: 0.88 and 0.99, respectively). There were no significant differences between groups for the variables depicted in Table 1, except for the optimal MVT ($p = 0.017$).

Table 2 shows two distinct models for 1RM prediction. The LD0, slope, individual MVT and the optimal MVT were all significant predictors of 1RM ($p < 0.0001$). For Model 1, the proportion of variance in 1RM explained

Table 1 Participant's dynamic strength performance and load–velocity relationship variables

	Training group ($n = 57$)	Testing group ($n = 19$)	p value
1RM (kg)	124.2 ± 32.4	131.6 ± 23.9	0.344
Relative 1RM	1.68 ± 0.35	1.75 ± 0.21	0.389
Individual MVT ($m.s^{-1}$)	0.28 ± 0.08	0.28 ± 0.07	0.782
Optimal MVT ($m.s^{-1}$)	0.36 ± 0.08	0.32 ± 0.08	0.017
Slope ($kg/m.s^{-1}$)	−116.53 ± 24.54	−107.61 ± 30.57	0.177
LD0 (kg)	166.5 ± 42.4	166.5 ± 35.0	0.717

Values are mean ± standard deviation

1RM one-repetition maximum, *MVT* minimum velocity threshold, *LD0* load at velocity zero (y-intercept of the load–velocity relationship)

Table 2 Multiple linear regression models for estimation of absolute one-repetition maximum (1RM)

	Stand β	SE	p value	Adjusted R^2
$Model_{IND}$—1RM (kg)				
LD0 (kg)	1.587	0.080	< 0.001	0.897
Slope ($kg/m.s^{-1}$)	0.810	0.094	< 0.001	
Individual MVT ($m.s^{-1}$)	–0.180	16.612	< 0.001	
$Model_{OPT}$—1RM (kg)				
LD0 (kg)	1.475	0.029	< 0.001	0.987
Slope ($kg/m.s^{-1}$)	0.538	0.036	< 0.001	
Optimal MVT ($m.s^{-1}$)	–0.381	5.661	< 0.001	

1RM one-repetition maximum, *LD0* load at zero velocity (*y* intercept of the load–velocity profile), *MVT* minimum velocity threshold, *Stand β* standardized regression coefficient, *SE* standard error

Models computed with data derived from the "training group" ($n = 57$)

Table 3 Validation of mixed models and individual load–velocity relationships for predicting free weight back squat one-repetition maximum

Population	Absolute error ± SD (%)	$\bar{x}$ difference ± 1.96 SD (kg)	Trend (R)
$Model_{IND}$: 1RM (kg) = 32.014 + 1.139*LD0 (kg) + 0.685*slope ($kg/m.s^{-1}$)–67.811*individual MVT ($m.s^{-1}$)			
	4.7 ± 3.4	2.8 ± 15.1	0.18
$Model_{OPT}$: 1RM (kg) = 44.485 + 1.059*LD0 (kg) + 0.455*slope ($kg/m.s^{-1}$)–124.256*optimal MVT ($m.s^{-1}$)			
	3.9 ± 2.8	−1.4 ± 11.4	0.07
LVR_{IND}	5.3 ± 4.1	−4.7 ± 15.9	0.68
LVR_{OPT}	2.7 ± 2.1	−0.5 ± 10.0	0.43

1RM one-repetition maximum, *LD0* load at zero velocity, *MVT* minimum velocity threshold, *R* Pearson's correlation coefficient of the difference between actual and estimated one-repetition maximum with the mean values of the one-repetition maximum

by LD0, slope and the individual MVT was 89.7% ($F = 160.07$; $p < 0.0001$). For Model 2, the proportion of variance in 1RM explained by LD0, slope and the optimal MVT reached 98.7% ($F = 1366.73$; $p < 0.0001$). Model 2 significantly increased the prediction power of 1RM estimation (R^2 change: 9%: F value change: 1206.66, $p < 0.0001$).

There was a method of estimation effect for 1RM ($F = 4.164$; $p = 0.017$). In specific, 1RM determined with $Model_{IND}$ was significantly different from the one derived from LVR_{IND} ($p = 0.019$). The absolute percent error between the actual and predicted 1RM was low for all methods, except for LVR_{IND} (Table 3). In addition, there was a method of estimation effect for the absolute percent errors ($F = 3.108$; $p = 0.034$). In specific, significant differences were found between LVR_{IND} and LVR_{OPT}. The one-sided t tests revealed that the mean difference between actual and estimated 1RM values was not statistically different from zero, except for $LVR_{IND.}$ The Pearson's correlation coefficients between the absolute difference and mean values were 0.18 ($p = 0.466$), 0.07 ($p = 0.768$), 0.68 ($p = 0.001$), 0.43 ($p = 0.061$) for estimates based on $Model_{IND}$, $Model_{OPT}$, $LVR_{IND,}$ and LVR_{OPT}, respectively (Table 3, Figs. 2, 3), suggesting heteroscedasticity for LVR_{IND}-based estimations.

Discussion

This study aimed to (1) examine if adding the individual or optimal MVT to a mixed-model approach improves the explained variance of 1RM in response to the free-weight back squat, and (2) to determine the validity of such models for 1RM prediction in this particular exercise, and (3) to compare the proposed mixed-models' 1RM estimations with the estimations directly extracted from the individual LVRs. Our findings can be summarized as follows: First, the inclusion of the individual MVT results in actual and predicted 1RMs that do not differ from each other. However, the use of the optimal, instead of the individual MVT, further improves the accuracy of these estimations. Second, despite the small magnitude of mean difference and absolute percent error obtained with $Model_{OPT}$, the limits of agreement (LoA) may still be too wide to track 1RM changes in circumstances involving a low margin of adaptability (e.g.

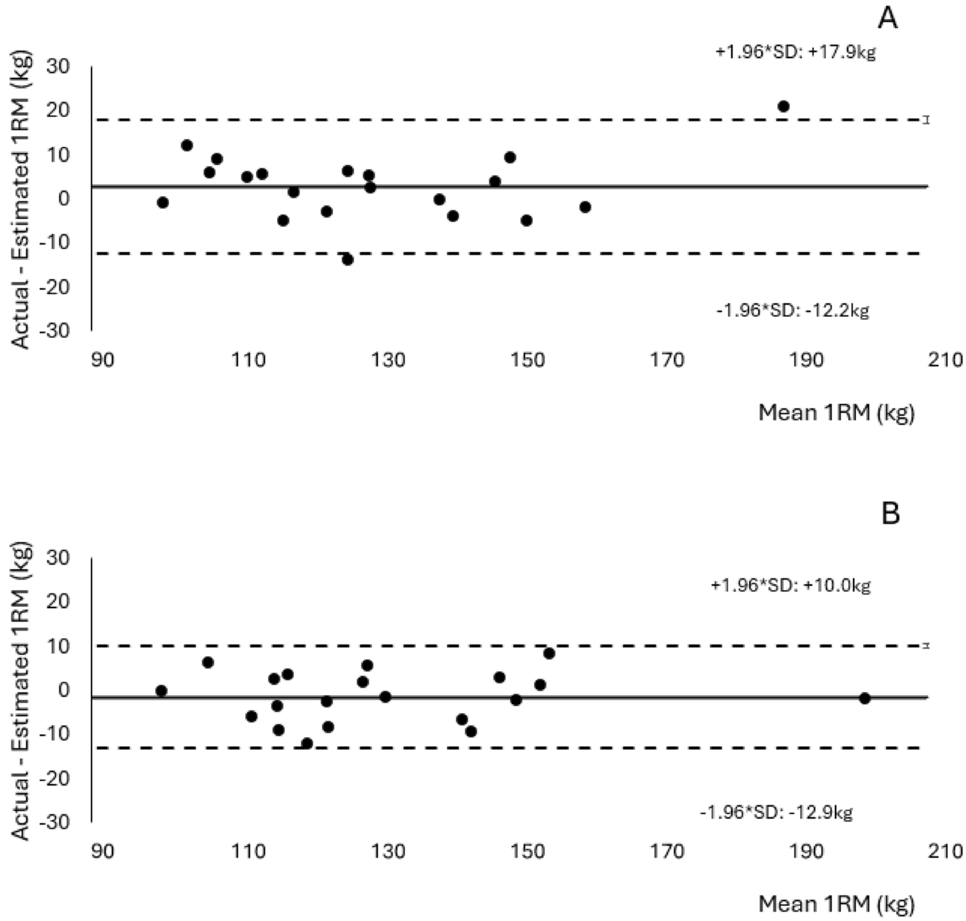

Fig. 2 Bland–Altman plot of the difference between actual and estimated one-repetition maximum (1RM) in response to the free-weight back squat with **A** Model$_{IND}$ and **B** Model$_{OPT}$ ($n = 19$). Solid and dashed lines represent mean difference and 95% limits of agreement (mean value ± 1.96 SDs), respectively

well-trained individuals). Regardless, both models displayed within-participant homoscedasticity, which indicates that the accuracy of 1RM prediction with these models does not interact with the individual levels of dynamic muscle strength. Third, the proposed models only enhance 1RM estimation accuracy if the individual MVT is selected, as similar absolute percent errors and mean differences were found between Model$_{OPT}$ and LVR$_{OPT}$.

Generalized equations for 1RM estimation were first proposed for the Smith-machine bench press exercise [12]. Despite being practical, generalized predictive equations lack the necessary individuality that is inherent to the LVR. In addition, they are influenced by a myriad of factors, such as sex, execution technique, movement pattern and strength levels [14, 15, 34, 35]. More recently, it was shown that the use of a mixed approach that combines a general equation with individual parameters obtained from the LVR (LD0 and slope) substantially improved the power of 1RM estimation for the free-weight back squat [18]. Therefore, on the present study, both these variables were included for modelling the prediction of 1RM.

Adding the individual MVT to LD0 and slope (Model 1) for estimating 1RM enhanced the model explained variance by ~ 6% and reduced the absolute percent error from 6.9 to 4.7%, when comparing to the model proposed by a previous report [18]. Additionally, the inclusion of the individual MVT also reduced the limits of agreement considerably (reduction of ~ 10 kg in the magnitude of over and underestimation). If estimations relying on the individual MVT are desired, our results suggest that a mixed model ought to be used instead of the individual LVR (which resulted in moderate errors, despite insignificant differences), as surprising as it may seem. However, it is important to note that the individual MVT displays poor between-day reliability, which ultimately means that different values might be inserted in the model on a different day, naturally affecting the accuracy of the estimation [17].

When compared with that seen when using the model based on the individual MVT, entering the individual optimal MVT (Model 2) increased the explained variance of 1RM to ~ 99% and reduced the absolute percent error to 3.9%, even though the optimal MVT from the "training" and "testing" groups were significantly different from one another. The optimal MVT has been proposed as a better alternative to the individual MVT [19]. Only one report tested the predictive capacity of the optimal MVT to

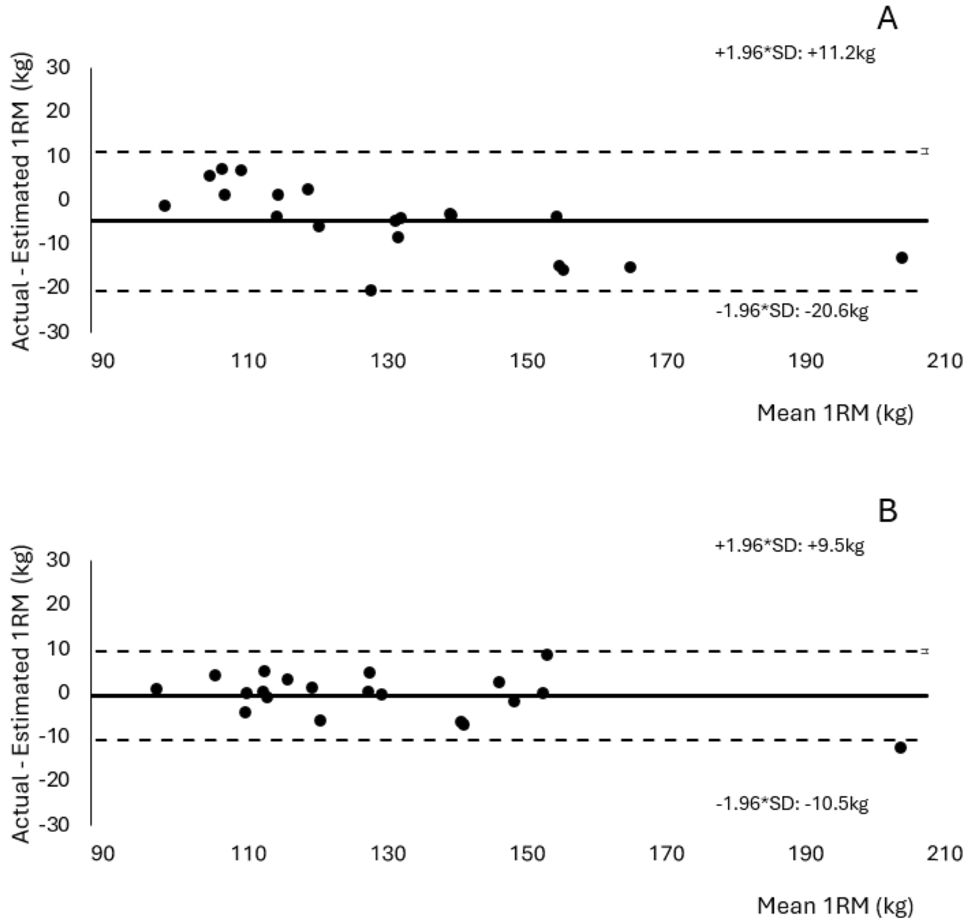

Fig. 3 Bland–Altman plot of the difference between actual and estimated one-repetition maximum (1RM) in response to the free-weight back squat with **A** LVR_{IND} and **B** LVR_{OPT} ($n = 19$). Solid and dashed lines represent mean difference and 95% limits of agreement (mean value ± 1.96 SDs), respectively

estimate the 1RM through the individual LVR of the free-weight back squat and found considerably better estimates when this velocity variable is used [20]. Therefore, taken together, it can be said that there is preliminary evidence that using the individual optimal MVT, instead of the individual MVT, allows for more accurate estimations of the free-weight back squat, regardless of the modelling approach (individual LVR or mixed model), and this is novel. This fact corroborates the notion that more accurate 1RM estimations can be obtained when entering a velocity value into the LVR that is greater than the average individual MVTs (0.3 $m.s^{-1}$) typically reported for the free-weight back squat in the available literature [6]. Furthermore, the similar outputs of $Model_{OPT}$ and LVR_{OPT} suggest that the optimal MVT may already be sensitive enough to partially account for individual characteristics that may affect the LVR. Despite this, it would be important to determine the long-term reliability of this particular variable. This information is fundamental to unravel whether a single determination of the individual optimal MVT might enable the subsequent estimation of 1RM on multiple instances over time.

According to the present results, dynamic strength does not seem to be a factor that significantly affects the accuracy of 1RM prediction with a mixed-model approach, and this indicates that both models can be used in male resistance trained subjects, regardless of their actual free-weight back squat 1RM. These results are in consonance with a previous report that provided a mixed model using only the LD0 and slope of the LVR [18]. In fact, even when the sample was divided into subgroups (stronger and weaker), a homoscedastic behavior of data dispersion was found [18]. Another report, using individual LVRs and the respective individual MVT also found linear and polynomial LVRs to attain homoscedastic free-weight back squat 1RM estimations, despite the wide LoA [36]. However, while the same was found for LVR_{OPT}, LVR_{IND} derived estimations were clearly affected by individual strength levels. This is in consonance with other prediction methods portrayed in the literature. For instance, in one previous report that estimated 1RM using the individual LVRs and their respective individual MVTs, it was found that the 1RM of stronger subjects tends to be consistently overestimated and that the 1RM of weaker subjects tends to be consistently underestimated [5]. With similar error trends, another report proposed a quadratic model based on the MCV at 80% 1RM for the free-weight back squat

1RM estimation [37]. As suggested by Fitas et al. (8), these discrepant findings may not only be explained by the different prediction approaches used, but also by the different sample sizes.

The prediction of 1RM for lower-limb exercises (i.e. squat and deadlift) with the LVR is consistently associated with inaccurate estimations and wide limits of agreement [5, 8, 17, 36, 37]. According to our results, especially for $Model_{OPT}$ and LVR_{OPT}, the limits of agreement were narrower than those previously reported in the literature (by ~ 10 kg). To our knowledge, this represents the lowest between-participant variability in the accuracy of the estimation of the free-weight back squat 1RM. In addition, as supported by the Bland–Altman analyses obtained for $Model_{OPT}$ and LVR_{OPT}, all subjects fell within the boundaries defined by the limits of agreement. Since this is atypical for lower-limb 1RM estimations [5, 36, 37], the present study further substantiates that the optimal MVT should be used in detriment of the individual MVT for improving the validity of predicted values. Most likely, the improved accuracy of 1RM estimations based on the optimal MVT relies on a better within-subject reliability of this particular variable.

Limitations

This study has at least five important limitations that must be acknowledged. First, since the 1RM prediction models were developed based on the free-weight back squat, they cannot be applied to other back-squat conditions (i.e. such as those involving different variations and execution techniques). This concept is substantiated by past data showing that the back-squat velocities associated with each relative load are higher for the ballistic variation and lower for the concentric-only technique [38]. Second, MCV data were collected using a specific brand of a linear position transducer. Therefore, the prediction accuracy of these models might be different when using a different linear-position transducer. Third, the velocities associated with eccentric phase of the movement were not measured. Thus, we cannot exclude the possibility that some variation in eccentric velocities might have affected the magnitude of the concentric MCV via a differential activation of the stretch–shortening cycle [39, 40]. Forth, the prediction models were obtained and tested using a group of individuals with a performance capability within the strength association phase (relative strength between 1.5 and 2.0) [41]. Whether these findings remain valid for those showing performance capabilities within the strength deficit or strength reserve phase remains largely unknown [41]. Fifth, the models proposed may only be valid for a short-term estimation purpose, as the long-term reliability of the optimal MVT has not yet been assessed.

Conclusions

This study provides preliminary evidence that the combination of LD0, slope and the MVT – individual or optimal – increases the predictive accuracy of the free-weight back squat within the context of a mixed-model approach. Furthermore, mixed modeling using the individual MVT proved to yield better accuracy when compared to the 1RM determination via the individual LVR, as the latter depicted mean differences significantly superior from zero. Notwithstanding, these findings indicate that strength and conditioning practitioners ought to rely on the optimal MVT for 1RM estimations, as substantiated by the smaller LoA. However, it should be noted that mixed modelling did not prove superior to the 1RM determination through the individual LVR when the optimal MVT was used. Thus, as the determination of the individual LVR is a more direct approach, relying on the individual LVR should be recommended when estimating the 1RM via the optimal MVT. Ultimately, and given the width of the LoA, on some individual cases, none of the suggested approaches may be able to detect small fluctuations in lower-body strength (of ~ 5%), such as those typically used to adjust load within a given training cycle.

Author contributions AF, PS and MG performed data collection. AF, PPC and GVM computed data analyses. AF, PS, MG, CVC, PPC and GVM wrote and edited the manuscript.

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Data availability The datasets generated during the present study are not publicly available due to the confidentiality of the data, but are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare they don't have any relation with companies or manufacturers. The results of the study are presented clearly, honestly, and without fabrication, falsification, or manipulation.

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

The declaration of Helsinki It can be used to replace the one provided in the Declarations section, in the following fashion: "The experimentaldesign complied with the principles set forth in the Declaration of Helsinki and was approved by the Faculty's EthicsCommittee (CEFMH Nº 16/2021) and all participants signed an informed consent.

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