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Lifting velocity predicts the maximum number of repetitions to failure with comparable accuracy during the Smith machine and free-weight prone bench pull exercises

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ABSTRACT

This study compared the accuracy of the fastest mean velocity from set ($MV_{fastest}$) to predict the maximum number of repetitions to failure (RTF) between 2 variants of prone bench pull (PBP) exercise (Smith machine and free-weight) and 3 methods (generalized, individualized multiple-point, and individualized 2-point). Twenty-three resistance-trained males randomly performed 2 sessions during Smith machine PBP and 2 sessions during free-weight PBP in different weeks. The first weekly session determined the RTF-$MV_{fastest}$ relationships and subjects completed single sets of repetitions to failure against 60-70-80-90%1RM. The second weekly session explored the accuracy of RTFs prediction under fatigue conditions and subjects completed 2 sets of 65%1RM and 2 sets of 85%1RM with 2 min of rest. The $MV_{fastest}$ associated with RTFs from 1 to 15 were greater for Smith machine compared to free-weight PBP ($F \geq 42.9$; $P < 0.001$) and for multiple-point compared to 2-point method ($F \geq 4.6$; $P \leq 0.043$). The errors when predicting RTFs did not differ between methods and PBP variants, whereas all RTF-$MV_{fastest}$ relationships overestimated the RTF under fatigue conditions. These results suggest that RTF–$MV_{fastest}$ relationships present similar accuracy during Smith machine and free-weight PBP exercises and it should be constructed under similar training conditions.

1. Introduction

Resistance training (RT) is an effective method to enhance different components of physical fitness from muscular strength to flexibility [1–3]. The intensity (*i.e.,* load lifted relative to an individual's maximal strength capacity) and volume (*i.e.,* number of sets and repetitions) are two of the most important variables that can be manipulated to induce selective gains in different strength manifestations [4,5]. Due to their relevance, researchers and coaches have attempted for decades to optimize the prescription methods of both variables [5,6]. One of the most popular RT prescription method is known as repetition maximum (RM) targets in which

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coaches prescribe the load (intensity) to match a specific number of repetitions to be completed before reaching muscular failure (*e.g.,* 10RM represents the load which subjects can complete 10 repetitions, no more, before reaching failure) and the repetition volume is prescribed based on the desired number of repetitions to leave in reserve [7]. However, a major limitation of RM targets is that it requires athletes to frequently perform sets to failure [7]. To solve this problem, the recording of the fastest mean velocity of the set ($MV_{fastest}$) has been recently proposed as an accurate predictor of the maximum number of repetitions that can be completed to failure (RTF) in exercises such as the bench press and prone bench pull (PBP) performed in a Smith machine [8].

Free-weight exercises are generally preferred in the context of sports performance due to their greater similarity with sport-specific actions and greater involvement of stabilizer muscles [5,9,10]. However, most applications of velocity-based training (VBT), including the ability to predict RTF from lifting velocity, have been mainly explored during exercises performed in a Smith machine [8,11–14]. This is because the available linear position transducers do not discriminate the direction of the movement (vertical, lateral, or anteroposterior) and the use of a Smith machine restricts the displacement of the barbell to the vertical direction potentially maximizing the accuracy of velocity recordings [15]. In this regard, the goodness-of-fit of general load-velocity relationships seems to be slightly stronger when the PBP is performed in a Smith machine (Pearson's multivariate coefficient of determination [r^2] = 0.95–0.96; standard error of the estimate [SEE] = 5.31–5.90%1RM) [12] compared to using free-weights (r^2 = 0.90–0.91; SEE = 6.27–6.56% 1RM) [16]. To date, no study has directly compared the accuracy of lifting velocity to predict RTF between Smith machine and free-weight exercises.

In previous studies, subjects were asked to perform sets to failure against multiple loads to determine the individualized RTF-$MV_{fastest}$ relationships [8,11]. However, due to the high linearity of individualized RTF-$MV_{fastest}$ relationships in the range of repetitions analyzed (from 1 to 20 repetitions), it seems reasonable to suggest that the two-point method could also be valuable for this VBT application. To date, only one study has explored the accuracy of RTF-$MV_{fastest}$ relationships under various levels of fatigue (four sets to failure of the Smith machine PBP exercise against the 75%1RM load) and demonstrated that RTF tends to be progressively overestimated with increased levels of fatigue [8]. Summing up, it is not only necessary to explore the accuracy of RTF-$MV_{fastest}$ relationships during free-weight exercises, but also to elucidate whether the testing procedure could be further simplified by asking subjects to perform sets to failure against only two distant loads (two-point method) and to determine whether the effect of fatigue on the overestimation of RTF from velocity recordings is maintained when greater (85%1RM) and lower (65%1RM) loads are lifted.

This study expanded the information regarding the potential application of lifting velocity to predict RTFs. Specifically, the objectives of this study were: (i) to compare the goodness-of-fit between the generalized and individualized RTF-$MV_{fastest}$ relationships obtained during the Smith machine and free-weight variants of the PBP exercise, (ii) to compare and associate the $MV_{fastest}$ values associated with each RTF (from 1 to 15 RTFs) between both individual estimation methods (multiple-point *vs.* two-point) and PBP exercises (Smith machine *vs.* free-weight), and (iii) to explore whether the accuracy in the prediction of RTFs is affected by fatigue (set 1 *vs.* set 2), the type of RTF-$MV_{fastest}$ relationship (generalized *vs.* multiple-point *vs.* two-point), and PBP exercise (Smith machine *vs.* free-weight). We hypothesized: (i) a higher goodness-of-fit for individualized compared to generalized RTF-$MV_{fastest}$ relationships [8,11] and for the Smith machine PBP compared to the free-weight PBP (ii) the $MV_{fastest}$ associated with each RTF would be comparable for the multiple- and two-point methods, but higher for the Smith machine PBP compared to the free-weight PBP [17], and (iii) both individualized RTF-$MV_{fastest}$ relationships (multiple-point and two-point) would present lower errors in the prediction of RTF than the generalized RFT-$MV_{fastest}$ relationship, although all of them would overestimate the RTF in fatigue conditions [8].

2. Material and methods

2.1. Participants

Twenty-three resistance-trained males (age = 25.0 ± 7.3 years [range: 18–45 years]; body height = 1.78 ± 0.07 m; body mass = 82.6 ± 22.7 kg; Smith machine PBP 1RM = 84.8 ± 12.9 kg [1.06 ± 0.17 normalized per kg of body mass]) participated in this study (data presented as means ± standard deviations [SD]). All subjects had 5.0 ± 4.7 years of RT experience and reported using the PBP in their regular training. No physical limitations or musculoskeletal injuries that could compromise testing were reported. Subjects were required to avoid any strenuous exercise over the course of the study. They were informed of the study procedures and signed a written informed consent form before the study onset. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board (approval no: 0557-N-22).

2.2. Experimental design

A crossover design was used to investigate the possibility of predicting RTF from the recording of lifting velocity during the Smith machine and free-weight PBP exercises. After a preliminary Smith machine PBP 1RM testing session, subjects undertook four experimental sessions, twice a week with at least 48 h of rest, over two consecutive weeks. In a counterbalanced order, subjects performed two sessions using the Smith machine PBP in one week, and two sessions using the free-weight PBP in another week. The first weekly session consisted of single sets of repetitions to failure separated by 5 min against four relative loads that were applied in the following order: 60%1RM, 90%1RM, 70%1RM, and 80%1RM. The second weekly session consisted of four sets of repetitions to failure (two randomized sets against the 65%1RM and two sets against the 85%1RM) separated by 2 min of rest. Subjects were always instructed to lift the barbell as fast as possible and received MV feedback from the first to the last repetition [8,18]. All sessions were conducted at the University's research laboratory, at the same time of the day for each subject (±3 h), and under similar environmental conditions (~22 °C and ~60% humidity) (Fig. 1).

2.3. Procedures

2.3.1. 1RM assessment (preliminary session)

The warm-up consisted of jogging, dynamic stretching, upper-body joint mobilization exercises, and two sets of five repetitions of the Smith machine PBP against 20 and 30 kg. The initial load of the incremental loading test was set at 40 kg, and it was progressively increased in 10 kg increments until the MV was lower than 0.80 $m \cdot s^{-1}$. From that moment, the load was increased in steps of five to one kg until the 1RM was directly achieved. Two repetitions were performed with light-moderate loads (MV $\geq$ 0.80 $m \cdot s^{-1}$) and one repetition with heavier loads (MV $<$ 0.80 $m \cdot s^{-1}$). Recovery time was set to 3 min for light-moderate loads and 5 min for heavier loads. Finally, subjects completed two sets of repetitions to failure separated by 5 min against the 60%1RM and 80%1RM for familiarization purposes [8].

2.3.2. Determination of RTF-$MV_{fastest}$ relationship (first weekly session)

The second and fourth sessions were identical, but a single PBP exercise (Smith machine or free-weight) was used in each session. The warm-up consisted of jogging, dynamic stretching, and upper-body joint-mobilization exercises, followed by one set of 10, three, and one repetition of the tested PBP with the 40%1RM, 60%1RM, and 80%1RM, respectively. After warming-up, subjects rested for 3 min, and then they performed single sets of repetitions to failure against four different loads in the following order: 60%1RM, 90% 1RM, 70%1RM, and 80%1RM. Rest periods of 5 min were implemented between successive sets.

2.3.3. Effect of fatigue on RTF prediction (second weekly session)

Each session began with the same warm-up described for the second and fourth sessions. Subjects performed two sets of repetitions to failure against the 65%1RM and another two sets against the 85%1RM. The loads were applied in randomized order, but the same sequence and absolute loads were maintained for individual subjects during both sessions. To ensure fatigue, rest periods of only 2 min were implemented between successive sets [8]. This analysis only included 22 subjects because one subject did not attend to the fifth testing session.

2.4. PBP technique

The PBP exercise was performed in a Smith machine (Multipower Fitness Line, Peroga, Murcia, Spain) or with a standard Olympic barbell (Rockstrong Bar, Ruster Fitness, Jaén, Spain). Subjects lied down in a prone position, with their chins touching the bench, and their elbows fully extended with a prone grip of the barbell slightly wider than shoulder width [8]. The telescopic holders of the Smith machine were positioned so that the barbell stopped exactly when both elbows were in full extension. The barbell was stopped on a bench during the free-weight PBP to maintain the same range of motion. From that initial position, subjects were instructed to pull the barbell as fast as possible until it contacted with the underside of the bench. When the barbell did not contact the underside of the bench (thickness of 11.0 cm) for two consecutive repetitions, the test ended and both repetitions were not considered [8]. The legs were held with a rigid strap on the calves. A validated linear velocity transducer (T-Force System version 3.70; Ergotech, Murcia, Spain) was used to determine the MV (*i.e.,* average velocity from the first positive velocity until the velocity is 0 $m \cdot s^{-1}$) [19]. Specifically, the MV of the fastest and last repetitions of the sets were used for subsequent analyses.

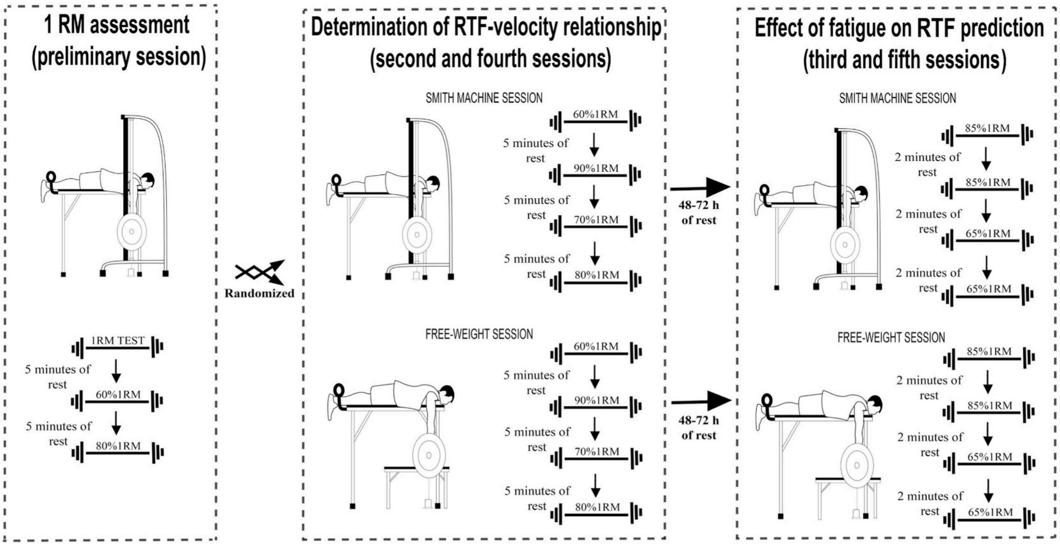

Fig. 1. Overview of the experimental design. 1RM, one-repetition maximum; RTF, maximum number of repetitions performed before achieving momentary muscular failure. Note that the order of the 65%1RM and 85%1RM loads in the third and fifth testing sessions was randomized.

2.5. Statistical analyses

Data are presented as means and SD, while the r^2 and SEE are presented through the median value and range. The normal distribution of the data was confirmed using the Shapiro-Wilk test ($P > 0.05$). One-way repeated-measures analysis of variances (ANOVA) were applied to compare RTF, $MV_{fastest}$ and MV_{last} between the sets performed against four relative loads (60-90-70-80%1RM) separately for each PBP exercise. Least-square linear regression models were used to determine the relationship between RTF and $MV_{fastest}$ using the data of the first weekly sessions [8,11]. Generalized RTF-$MV_{fastest}$ relationships were obtained by pooling together the data from all subjects (23 subjects × 4 sets = 92 data points) [8,11], while individualized RTF-$MV_{fastest}$ relationships were computed separately for each subject considering the data points acquired from the four loads (*i.e.,* multiple-point method [60-90-70-80%1RM]) or only the two most distant loads (*i.e.,* two-point method [60–90%1RM]). The goodness-of-fit of generalized and individualized RTF-$MV_{fastest}$ relationships were evaluated through the r^2 and SEE [8,11].

A two-way repeated-measures ANOVA (method [multiple-point *vs.* two-point] × PBP exercise [Smith machine *vs.* free-weight]) was used to compare the $MV_{fastest}$ associated with each predicted RTF [8,11]. The Pearson's product-moment correlation coefficient (r) was used to quantify the association of the $MV_{fastest}$ attained at each RTF between both methods and PBP exercises. The criteria for interpreting the magnitude of the r coefficients were as follows: *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) [20]. The magnitude of the differences was also assessed by the Cohen's d effect size (ES), which was interpreted using the following scale: *trivial* (<0.20), *small* (0.20–0.59), *moderate* (0.60–1.19), *large* (1.20–1.99), and *very large* (≥2.00) [20].

Finally, a three-way repeated-measures ANOVA (method [generalized *vs.* multiple-point *vs.* 2-point] × PBP exercise [Smith machine *vs.* free-weight] × set [set 1 *vs.* set 2]) was applied to compare the raw and absolute errors obtained for the prediction of RTF separately for the 65%1RM and 85%1RM loads. The Greenhouse-Geisser correction was used when the Mauchly's sphericity test was violated and pairwise differences were identified using Bonferroni post-hoc corrections. The analyses were performed by the software package SPSS (IBM SPSS version 25.0, Chicago, IL, USA). Alpha was set at $P \leq 0.05$.

3. Results

Regardless of the PBP exercise, the increase in the load was accompanied by a decrease in RTF and $MV_{fastest}$, but no significant differences were found for MV_{last} (Table 1). The goodness-of-fit of the generalized RTF-$MV_{fastest}$ relationship was stronger for the Smith machine PBP ($r^2 = 0.79$; SEE = 5.4 repetitions) than for the free-weight PBP ($r^2 = 0.67$; SEE = 6.6 repetitions) (Fig. 2). The individualized RTF-$MV_{fastest}$ relationships were always stronger than the generalized RFT-$MV_{fastest}$ relationships and in this case the goodness-of-fit was comparable for the Smith machine PBP ($r^2 = 0.96$ [0.86, 1.00]; SEE = 2.8 repetitions [0.6, 7.8 repetitions]) and free-weight PBP ($r^2 = 0.94$ [0.79, 1.00]; SEE = 3.0 repetitions [0.5, 9.5 repetitions]) (Fig. 2).

The method × PBP exercise interaction did not achieve statistical significance for any RTF ($F \leq 0.2$; $P \geq 0.600$). The main effects of the PBP exercise ($F > 0.1$; $P < 0.001$) and method ($F > 0.1$; $P \leq 0.043$) were significant for all RTFs due to the higher MV values associated with each RTF for the Smith machine PBP and multiple-point method compared to the free-weight PBP and 2-point method, respectively (Table 2). The MV values associated with each RTF presented *very large* to *nearly perfect* correlations between the multiple- and 2-point methods during both the Smith machine PBP ($r = 0.88$ [0.87, 0.91]) and free-weight PBP ($r = 0.94$ [0.93, 0.94]), while the magnitude of the differences were *small* (Smith machine PBP: ES = −0.47 [−0.49, −0.41]; free-weight PBP: ES = −0.35 [−0.36, −0.29]). The correlations of the MV values associated with each RTF between the PBP exercises ranged from *moderate* to *very large* (multiple point-method: $r = 0.75$ [0.55, 0.80]; 2-point method: $r = 0.59$ [0.32, 0.70]), and the magnitude of the differences were *moderate* to *small* (multiple-point method: ES = −0.59 [−0.69, −0.36]; 2-point method: ES = −0.65 [−0.69, −0.43]) (Fig. 3).

None of the three- or two-way interactions reached statistical significance for either absolute ($F \leq 3.0$; $P \geq 0.095$) or raw ($F \leq 4.1$; $P \geq 0.053$) errors. Regarding the absolute errors, only the main effect of set reached statistical significance against the 85%1RM ($F = 16.0$; $P = 0.001$) due to greater errors in the second compared to the first set (Fig. 4). Regarding the raw errors, only the main effect of set reached statistical significance against both the 65%1RM and 85%1RM ($F \geq 13.3$; $P \leq 0.001$) due to greater overestimation of RTF in the second compared to the first set (Fig. 4).

Table 1

Comparison of the number of repetitions performed before reaching momentary muscular failure (RTF) and the mean velocity of the fastest ($MV_{fastest}$) and last (MV_{last}) repetition of sets performed against four relative loads in Smith machine and free-weight prone bench pull (PBP) exercises.

Variable	PBP exercise	60%1RM	70%1RM	80%1RM	90%1RM	ANOVA
RTF	Smith machine	32.1 ± 9.0	19.3 ± 5.0^{a}	$10.0 \pm 3.0^{b,c}$	$4.7 \pm 2.3^{a,b,c}$	$F = 242.0$; $P < 0.001$
	Free-weight	30.6 ± 9.8	17.3 ± 5.4^{a}	$8.8 \pm 3.0^{b,c}$	$4.1 \pm 2.1^{a,b,c}$	$F = 167.7$; $P < 0.001$
$MV_{fastest}$ ($m \cdot s^{-1}$)	Smith machine	0.95 ± 0.06	0.81 ± 0.06^{a}	$0.70 \pm 0.07^{b,c}$	$0.60 \pm 0.07^{a,b,c}$	$F = 528.2$; $P < 0.001$
	Free-weight	0.88 ± 0.08	0.76 ± 0.09^{a}	$0.66 \pm 0.09^{b,c}$	$0.56 \pm 0.09^{a,b,c}$	$F = 281.8$; $P < 0.001$
MV_{last} ($m \cdot s^{-1}$)	Smith machine	0.52 ± 0.10	0.53 ± 0.09	0.50 ± 0.06	0.50 ± 0.05	$F = 1.9$; $P = 0.128$
	Free-weight	0.50 ± 0.11	0.51 ± 0.09	0.49 ± 0.06	0.46 ± 0.07	$F = 2.5$; $P = 0.087$

Data are presented as mean ± standard deviation. 1RM, one-repetition maximum; ANOVA, analysis of variance; F, Snedecor's F; *P*, *P*-value; [a], significantly different than 60%1RM; [b], significantly different than 70%1RM; [c], significantly different than 80%1RM.

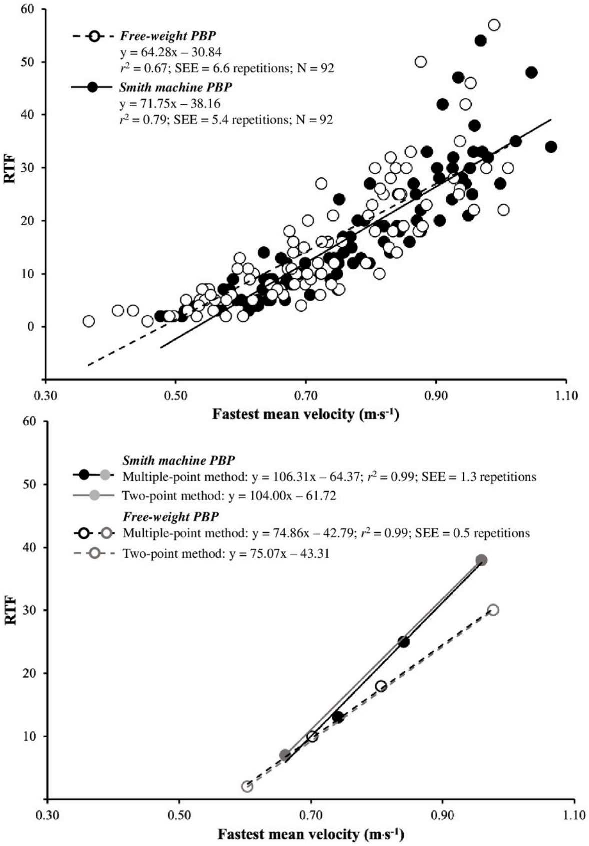

Fig. 2. Upper panel represents the generalized relationship between the maximum number of repetitions performed before achieving momentary muscular failure (RTF) and the fastest mean velocity of the set ($MV_{fastest}$) during the Smith machine (filled dots and straight lines) and free-weight (open dots and dashed lines) prone bench pull (PBP) exercises. Lower panel represents the individualized RTF-$MV_{fastest}$ relationship of a representative participant obtained using the multiple- and 2-point methods during the Smith machine and free-weight PBP exercises. r^2, Pearson's multivariate coefficient of determination; SEE, standard error of the estimate; N, numbers of trials included in the regression analysis.

4. Discussion

The present study attempts to gather information about the potential use of lifting velocity to predict RTFs using different methods (generalized *vs.* multiple-point *vs.* two-point) and PBP exercises (Smith machine *vs.* free-weight) under various levels of fatigue. The main findings of the study revealed that (i) individualized RTF-$MV_{fastest}$ relationships presented a higher goodness-of-fit than the generalized RTF-$MV_{fastest}$ relationship being the differences between the methods more accentuated during the free-weight PBP than during the Smith machine PBP, (ii) the $MV_{fastest}$ associated with different RTFs were greater for the Smith machine PBP and multiple-point method compared to the free-weight PBP and two-point method, respectively, (iii) the raw and absolute errors when predicting RTFs during sets performed against the 65%1RM and 85%1RM were comparable for the three methods and two PBP variants, and (iv) all RTF-$MV_{fastest}$ relationships overestimated the RTF under fatigue conditions. These results suggest that RTF-$MV_{fastest}$ relationships allow predicting RTFs with comparable accuracy during Smith machine and free-weight exercises, while the RTF-$MV_{fastest}$ relationship should preferably be determined under fatigue conditions resembling those experienced during RT.

Our first hypothesis was confirmed because both PBP exercises always showed greater goodness-of-fit for individualized compared to generalized RTF-$MV_{fastest}$ relationships. These findings are in line with Miras-Moreno et al. [8] who reported during the Smith machine PBP a lower goodness-of-fit for the generalized ($r^2 = 0.70$; SEE = 3.6 repetitions) compared to individualized ($r^2 = 0.96$ [0.83–1.00]; SEE = 1.7 repetitions [0.3–4.7]) RTF-$MV_{fastest}$ relationships. The increased differences between the generalized and individualized RTF-$MV_{fastest}$ relationships for the free-weight PBP compared to the Smith-machine PBP suggests that the inter-individual variability is larger for free-weight exercises. However, contrary to our hypothesis and the general belief that VBT applications are compromised with free-weight exercises, the goodness-of-fit of individualized RTF-$MV_{fastest}$ relationships was comparable for both PBP variants. This finding suggests that the accuracy of individualized RTF-$MV_{fastest}$ relationships is similar for Smith machine and free-weight exercises.

Supporting our second hypothesis, the $MV_{fastest}$ associated with each RTF was greater for the Smith machine PBP compared to the free-weight PBP. This may be explained because machine-based equipment requires less inter-muscular coordination contributing to generate more force in the direction of the movement [9,10,21,22]. Consequently, the loads associated with the same $MV_{fastest}$ were

Table 2

Comparison of the fastest mean velocity of the set associated with each maximum number of repetitions performed before reaching momentary muscular failure (RTF) between methods and prone bench pull (PBP) exercises.

Smith machine			Free-weight			ANOVA	
RTF	Multiple-point method	Two-point method	Multiple-point method	Two-point method	Method	PBP exercise	Interaction
1	0.57 ± 0.06	0.55 ± 0.06	0.55 ± 0.08	0.52 ± 0.08	$F = 4.6$; $P = 0.043$	$F = 42.9$; $P < 0.001$	$F = 0.2$; $P = 0.600$
2	0.58 ± 0.05	0.56 ± 0.05	0.56 ± 0.07	0.54 ± 0.08	$F = 5.1$; $P = 0.034$	$F = 42.5$; $P < 0.001$	$F = 0.2$; $P = 0.615$
3	0.60 ± 0.05	0.57 ± 0.05	0.58 ± 0.07	0.55 ± 0.08	$F = 5.6$; $P = 0.027$	$F = 42.0$; $P < 0.001$	$F = 0.2$; $P = 0.631$
4	0.61 ± 0.05	0.59 ± 0.05	0.59 ± 0.07	0.56 ± 0.08	$F = 6.0$; $P = 0.022$	$F = 41.4$; $P < 0.001$	$F = 0.2$; $P = 0.648$
5	0.62 ± 0.05	0.60 ± 0.05	0.60 ± 0.07	0.58 ± 0.07	$F = 6.3$; $P = 0.019$	$F = 40.7$; $P < 0.001$	$F = 0.1$; $P = 0.668$
6	0.64 ± 0.05	0.62 ± 0.05	0.61 ± 0.07	0.59 ± 0.07	$F = 6.6$; $P = 0.017$	$F = 39.9$; $P < 0.001$	$F = 0.1$; $P = 0.668$
7	0.65 ± 0.04	0.63 ± 0.04	0.63 ± 0.07	0.60 ± 0.07	$F = 6.8$; $P = 0.016$	$F = 39.1$; $P < 0.001$	$F = 0.1$; $P = 0.710$
8	0.66 ± 0.04	0.64 ± 0.04	0.64 ± 0.07	0.62 ± 0.07	$F = 6.8$; $P = 0.016$	$F = 38.1$; $P < 0.001$	$F = 0.1$; $P = 0.734$
9	0.68 ± 0.04	0.66 ± 0.04	0.65 ± 0.07	0.63 ± 0.07	$F = 6.8$; $P = 0.016$	$F = 37.1$; $P < 0.001$	$F < 0.1$; $P = 0.759$
10	0.69 ± 0.04	0.67 ± 0.04	0.66 ± 0.07	0.64 ± 0.07	$F = 6.7$; $P = 0.017$	$F = 36.0$; $P < 0.001$	$F < 0.1$; $P = 0.785$
11	0.70 ± 0.04	0.68 ± 0.04	0.68 ± 0.07	0.66 ± 0.07	$F = 6.5$; $P = 0.018$	$F = 34.8$; $P < 0.001$	$F < 0.1$; $P = 0.812$
12	0.72 ± 0.04	0.70 ± 0.04	0.69 ± 0.07	0.67 ± 0.07	$F = 6.3$; $P = 0.020$	$F = 33.5$; $P < 0.001$	$F < 0.1$; $P = 0.840$
13	0.73 ± 0.04	0.71 ± 0.04	0.70 ± 0.07	0.68 ± 0.07	$F = 6.0$; $P = 0.022$	$F = 32.2$; $P < 0.001$	$F < 0.1$; $P = 0.868$
14	0.74 ± 0.04	0.73 ± 0.05	0.71 ± 0.07	0.69 ± 0.07	$F = 5.8$; $P = 0.024$	$F = 30.8$; $P < 0.001$	$F < 0.1$; $P = 0.896$
15	0.76 ± 0.04	0.74 ± 0.05	0.73 ± 0.07	0.71 ± 0.07	$F = 5.5$; $P = 0.028$	$F = 29.3$; $P < 0.001$	$F < 0.1$; $P = 0.925$

Data are presented as means ± standard deviations. F, Snedecor's F; *P*, *P*-value.

higher for the Smith machine PBP and the higher loads could explain the lower RTFs for the same $\text{MV}_{\text{fastest}}$. However, contrary to our second hypothesis, the $\text{MV}_{\text{fastest}}$ associated with each RTF was greater for the multiple-point method compared to the two-point method. Of note is that the RTF-$\text{MV}_{\text{fastest}}$ relationship was obtained with less fatigue using the two-point method (two sets to failure) than the multiple-point method (four sets to failure). Therefore, the higher $\text{MV}_{\text{fastest}}$ for each RTF using the multiple-point method is not surprising as this and previous study have shown that during the PBP exercise the increase in fatigue promotes a greater reduction in RTF than in $\text{MV}_{\text{fastest}}$ [8]. These results suggest that the two-point method could be the preferred option to estimate RTFs during RT sessions with low-moderate levels of fatigue in which lifters do not generally complete sets of repetitions to failure. Therefore, in addition to estimating the 1RM through the load-velocity relationship [13] or assessing the force-velocity [23] and load-velocity relationship variables [24], the results of this study suggest that the two-point method can also be used as a quicker and less prone to fatigue method for assessing the RTF-$\text{MV}_{\text{fastest}}$ relationship.

The high correlations between PBP variants (Smith machine and free-weights) and methods (multiple-point and two-point) for the $\text{MV}_{\text{fastest}}$ associated with each RTF suggest that RTF-$\text{MV}_{\text{fastest}}$ relationships are subject-specific. However, despite these results and the greater goodness-of-fit for individualized compared to generalized RTF-$\text{MV}_{\text{fastest}}$ relationships, contrary to our third hypothesis, the magnitude of the errors in the prediction of RTFs did not differ between the individualized (multiple-point or two-point) and generalized RTF-$\text{MV}_{\text{fastest}}$ relationships. The only significant difference regarding RTF prediction errors was that they were higher for the second set compared to the first set. These results suggest that fatigue affects more RTF than $\text{MV}_{\text{fastest}}$. In addition, the general overestimation of RTF could be explained by the greater fatigue in which the sets were performed in the second weekly session (only 2 min of inter-set rest) compared to the first weekly session in which the RTF-$\text{MV}_{\text{fastest}}$ relationships were established (5 min of inter-set rest). Therefore, it seems logical to construct the RTF-$\text{MV}_{\text{fastest}}$ relationship that coincides as much as possible with the level of fatigue experienced during RT, being advisable to use the two-point method with a long inter-set rest period (*e.g.,* 10 min) when this RT prescription method is intended to be used during low to moderate fatigue RT sessions.

The main limitation of this study is that we explored the possibility of predicting RTF in a session in which the level of fatigue was greater that the experienced in the session in which the RTF-$\text{MV}_{\text{fastest}}$ relationships were assessed. This is problematic because in our sample the RTF-$\text{MV}_{\text{fastest}}$ relationship was sensitive to fatigue. Therefore, future studies should try to equalize the fatigue levels for the testing and training sessions to elucidate whether the prediction capabilities of RTF-$\text{MV}_{\text{fastest}}$ relationships are increased. Finally, it should be explored whether the effect of fatigue on the RTF-$\text{MV}_{\text{fastest}}$ relationship is observed in other RT exercises and in individuals with more RT experience.

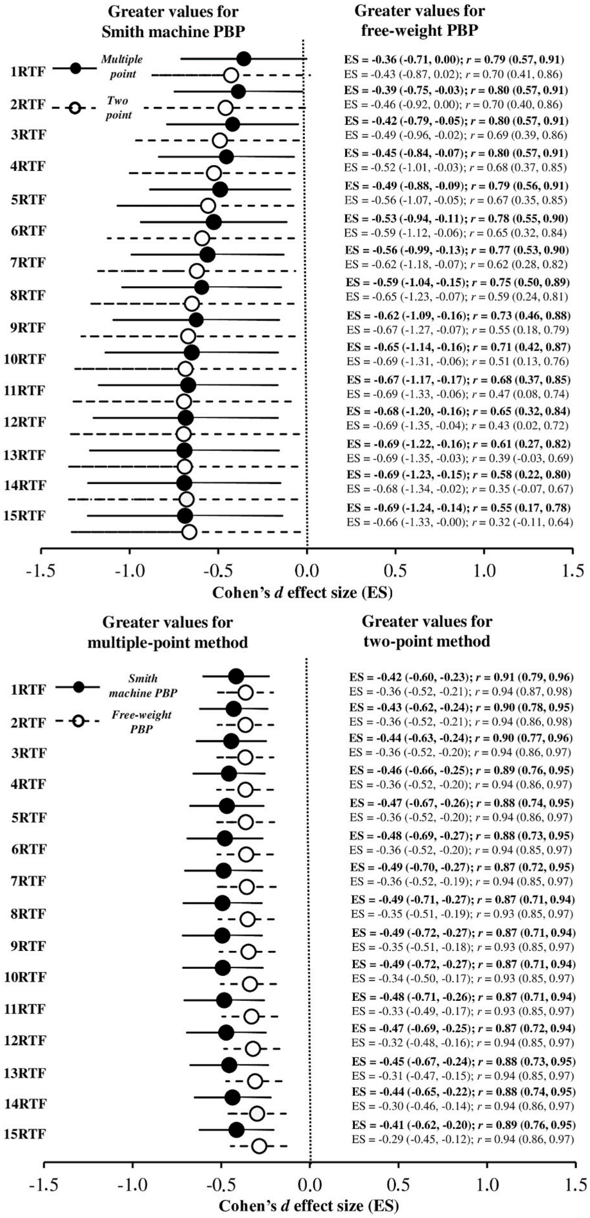

Fig. 3. Comparisons and associations of the fastest mean velocity of the set associated with each maximum number of repetitions performed before reaching momentary muscular failure (RTF) between methods (multiple-point *vs.* 2-point; upper-panel) and prone bench pull (PBP) exercises (Smith machine *vs.* free-weight; lower-panel). ES, Cohen's *d* effect size; *r*, Pearson's product-moment correlation coefficient.

5. Conclusions

RTF-$MV_{fastest}$ relationships allow RTFs to be predicted with similar accuracy during the Smith machine and free-weight variants of the PBP exercise, opening up the possibility of using this RT prescription method during free-weight RT exercises. However, it is important to note that RTF-$MV_{fastest}$ relationships are sensitive to fatigue with greater fatigue levels affecting RTF more than $MV_{fastest}$. Therefore, RTF-$MV_{fastest}$ relationships should be determined under fatigue conditions resembling those experienced during training. The assessment of RTF and $MV_{fastest}$ against only two different loads (*e.g.,* 90%1RM and 70%1RM) with long inter-set rest periods (*e.g.,* 10 min) is recommended to obtain individualized RTF–$MV_{fastest}$ relationships to be used during RT sessions in which the level of fatigue is low or moderate (*e.g.,* sets not performed to failure). The RTF-$MV_{fastest}$ relationship should preferably be determined under fatigue conditions (*e.g.,* not considering the first two sets to failure) when is intended to be used during RT sessions with high levels of effort (*i. e.,* multiple sets performed to failure).

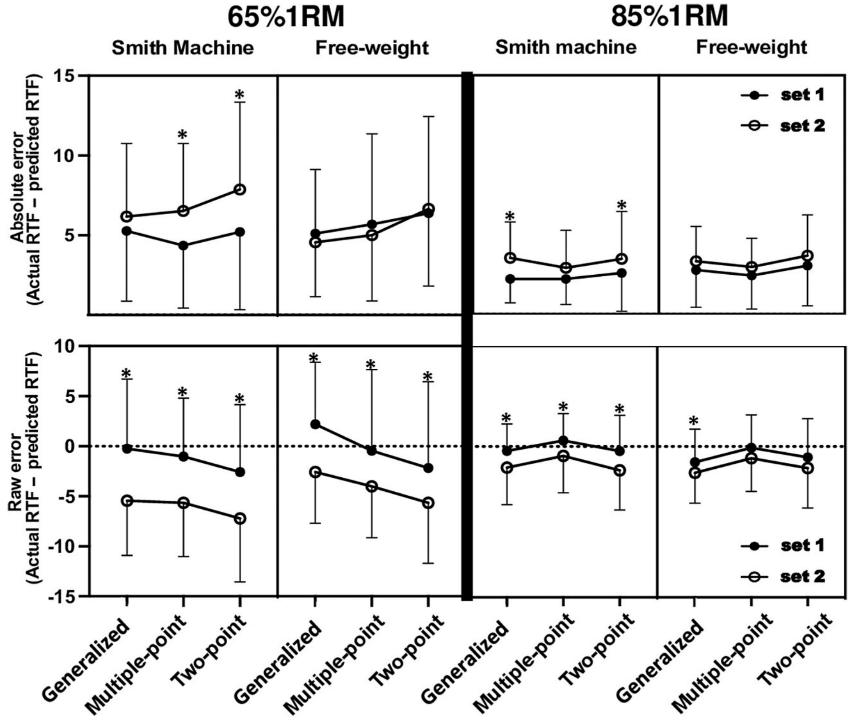

Fig. 4. Comparison of the raw and absolute errors when predicting the maximum number of repetitions performed before achieving momentary muscular failure (RTF) between different methods (generalized *vs.* multiple-point *vs.* 2-point), prone bench pull (PBP) exercises (Smith machine *vs.* free-weight) and sets (set 1 *vs.* set 2) during sets performed against the 65% and 85% of the one-repetition maximum (1RM). Data are presented as means ± standard deviations. *, significant greater errors during the RTF prediction in the set 2 compared to the set 1.

Author contribution statement

Sergio Miras-Moreno - performed the experiments; contributed to the conception and design of the experiments; analyzed and interpreted the data; contributed to reagents, materials, analysis tools or data; wrote the paper.

Alejandro Pérez-Castilla and Amador García-Ramos - contributed to the conception and design of the experiments; analyzed and interpreted the data; contributed to reagents, materials, analysis tools or data; wrote the paper.

Francisco Javier Rojas-Ruiz, - contributed to reagents, materials, analysis tools or data; wrote the paper.

Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sergio Miras-Moreno reports financial support was provided by Spanish Ministry of University. Francisco Javier Rojas-Ruiz reports financial support was provided by Spanish Ministry of Science and Innovation.

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