Thieme

Where does the One-Repetition Maximum Exist on the Force-Velocity Relationship in Squat?

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ABSTRACT

The aim was to determine the position of the one-repetition maximum (1RM) squat point on the force-velocity (F-V) relationship obtained during squat jump (SJ). Ten healthy athletes performed a 1RM squat during which ground reaction force and lower-limb extension velocity were measured, and six loaded SJs to determine individual F-V relationship. The goodness of fit of the linear F-V relationship with or without the 1RM point was tested. The vertical and horizontal coordinates were determined relative to the theoretical maximal force (F0) and the highest loaded SJ (load of 44.5 ± 4.6 % 1RM). The goodness of fit of the individual F-V relationship did not differ with or without the 1RM condition, even if the 1RM point was slightly below the curve (− 5 ± 5 %, P = 0.018). The 1RM point can be considered as a point of the F-V relationship. The velocity (0.22 ± 0.05 m.s^{-1}) of the 1RM point corresponded to ~30 % of the velocity reached during the highest loaded SJ. The force developed in the 1RM condition was ~16 % higher than during the highest loaded SJ and ~11 % lower than F0. This finding underlines the difference between F0 and the 1RM condition.

Abbreviations

1RM	One-repetition maximum
F	Mean force developed during the 1RM squat estimated with simple computations
F_{SJ}	Mean force developed during a squat jump estimated with the simple method
F_{1RM}	Mean force developed during the 1RM squat measured with the force plate
F0	The theoretical maximal force that lower limbs could produce over one extension at null velocity
$F0_{SJ}$	The theoretical maximal force that lower limbs could produce over one extension at null velocity extrapolated from The force-velocity relationship obtained in squat jumps
F-V	Force-velocity
F-V_{SJ}	Force-velocity relationship obtained in squat jumps
F-V_{1RM}	Force-velocity relationship obtained in squat jumps comprising the one-repetition maximum squat condition
SJ	Squat jump
P-V	Power-velocity
V	Mean velocity reached during the 1RM squat estimated with the simple computations
V0	The theoretical maximal velocity at which lower limbs could extend against no constraints
$V0_{SJ}$	The theoretical maximal velocity at which lower limbs could extend against no constraints extrapolated from the force-velocity relationship obtained in squat jumps

V_{1RM} mean lower-limb extension velocity reached during the 1RM squat measured with the motion analysis

V_{SJ} mean velocity reached during a squat jump estimated with the simple field method

Introduction

Ballistic movements, such as jumps, sprint starts, changes of direction (e. g., side-steps), are keys to successful performance in a range of sporting activities, notably in team sports, track and field, and combat sports, because they are often at the center of game-winning actions. According to the fundamental laws of dynamics, success in such explosive effort partly depends on the force developed by lower-limb extensor muscles. The human capacity to produce force during concentric lower limb extensions is well described by the linear force-velocity (F-V) and the parabolic power-velocity (P-V) relationships [4, 21, 31, 35]. These relationships characterize the mechanical limits of the entire lower-limb neuromuscular system and are well summarized through three parameters: the theoretical maximal force that lower limbs could produce over one extension at null velocity (F0), the theoretical maximal velocity at which they could extend against no constraints (V0), and the maximal power output they can develop over one extension. Graphically, F0 and V0 correspond to the force axis and velocity axis intercepts of the linear F-V relationship curve, respectively, and the maximal power output corresponds to the apex of the parabolic P-V relationship. Moreover, the slope of the F-V relationship (computed as the negative ratio of F0 to V0) represents the individual F-V mechanical profile of the lower-limb neuromuscular system and describes its orientation towards force or velocity qualities.

Ballistic performances have been recently shown, through biomechanical modeling [33, 35] and experimental results [31, 32], to depend on both the maximal power output and the individual F-V profile. Evaluating the entire individual F-V relationship, and not only maximal power capacity, is consequently of great interest for sport practitioners. It requires the measurement of force and velocity during ballistic lower limb extensions, e. g., squat jumps (SJ) against different resistances or loads (e. g., five or six different loads). Usually, force plates, optical encoders or video analyses are used to accurately measure and assess different mechanical parameters [9, 16, 30]. Given that the equipment used in academic research is not often readily available to sport practitioners, is both expensive and requires specific data processing skills, a simple method has been proposed and validated for the evaluation of the F-V and P-V relationships during vertical jumps directly in the field [14, 30]. This simple method has even recently been implemented in a smartphone application validated to accurately measure jump height [3]. However, the practical application of laboratory and simple field methods has shown the same limit: the restricted range of the force and velocity data used to determine the linear F-V relationship. For instance, the average push-off velocity values over different loaded conditions in studies using laboratory methods have ranged approximately from 0.5 to 1.3 $m.s^{-1}$, whereas the whole F-V relationship usually ranged from 0 to 2.6 $m.s^{-1}$ [5, 9, 30]. For the previously mentioned simple field method [32], an aerial phase (jump) is necessary to compute force and velocity outputs, whatever the load condition, and the minimum load corresponds to the body mass of the athlete performing the assessment. Consequently, the average push-off velocity values measured using such a method typically range from ~0.5 to 1.5 $m.s^{-1}$ [14, 23, 31], and as such represent a limited range of force and velocity values. Overall, whatever the method used, only ~30 % of the whole range of velocity values associated with the F-V relationship are usually covered by experimental points. As a consequence, some of the mechanical variables obtained (F0 and V0) are largely extrapolated, which makes them highly sensitive to small experimental variations inherent to the measurements. This in turn could alter the validity and the high reliability of these parameters [9, 21].

One conceivable solution to this issue would be the addition of points to the extremes of the F-V relationship. To increase the F-V spectrum of measured values, the mechanical constraints opposed to the movement have to be modulated (increased or decreased) to reach the targeted movement velocities [10, 25]. On the force side of the F-V relationship, the highest force-lowest velocity combination points could theoretically be obtained by maximizing resistive forces (i. e., maximum load able to be moved during a squat). In practice, the maximal load that an individual is able to lift corresponds to the "one-repetition maximum" (1RM; defined as the load that can be lifted once with correct lifting technique). The 1RM is commonly used as an indicator of dynamic maximal strength, which is a reference to express training loads and to quantify strength gain [3], and has consequently been widely investigated. However, to the authors' best knowledge, no research has been performed assessing mechanical outputs during the 1RM squat concomitantly with determining the F-V relationship. So, little information is available about kinetic and kinematic data during the 1RM squat and its link with the F-V relationship. In previous studies, the average velocity reached during 1RM squat ranged from 0.25 to 0.33 $m.s^{-1}$ for a full squat or a half-squat [7, 19, 20], whereas, to our knowledge, ground reaction force data have not been reported for such exercises. Thus, it would be of interest to measure the force and velocity outputs during a 1RM squat to obtain more information about the position of the 1RM-associated F-V values along the F-V curve. In particular, this would help verify its theoretical alignment with the other points, as recently supposed by Picerno et al. (2016), to predict 1RM from F-V and load-velocity relationships [28]. It is worth noting that the 1RM and F0 variables present similar practical meaning: the maximal force an athlete can produce during maximal-intensity lower limb extension. These two variables have never been directly compared within the same individuals, notably due to the difference in mechanical entities (force versus load), but their correlation has often been tested, and high and significant but not perfect correlations have been reported (correlation coefficients ranging from 0.80 to 0.94 [9, 12, 38]). This suggests that these two variables, even if they can be both interpreted as lower-limb dynamic maximal force indexes, do not represent exactly the same output from mechanical and practical standpoints. Thus, positioning the 1RM point on the F-V relationship would clarify the link between these two dynamic maximal strength indexes often used in numerous practices and scientific studies [6, 27]. Moreover, although the F-V relationship has been shown as linear in multi-joint tasks from the first study on lower limb extension [5] to more recent confirmations [4, 11, 21, 35], this linearity is often challenged, notably on the basis that the F-V relationship on mono-articular movement or on isolated muscle is curvilinear [13, 39], but also due to the restricted range of experimental points used to derive the full F-V spectrum [9, 21]. Consequently, using extreme experimental points, such as the 1RM point, to plot the F-V relationship would help better clarify the linearity of the F-V relationship in such movements.

The aim of this study was to test whether the 1RM point is aligned with the linear F-V relationship obtained during loaded SJs, and if so, to determine its position along the F-V relationship, notably compared to the F0 value. The hypotheses were that i) the 1RM squat point is aligned with the F-V relationship obtained in SJ, because the 1RM squat movement is similar to loaded or unloaded SJs, only differing in the higher external load; and that ii) the 1RM point is closer to F0 than the highest loaded SJ condition habitually used, because the velocity reached during a 1RM squat is very low, even if not negligible [7, 19, 20]. If these two hypotheses were confirmed, the third aim of this study was to test the validity of simple computations to determine force and velocity during a 1RM squat test to complete the F-V relationship obtained using a simple computation method. The application of dynamic principles applied to the body center of mass during a 1RM squat was supposed to lead to valid estimations of force and velocity values.

Methods

Subjects

Ten healthy male subjects (age = 24 ± 5 years, mass = 79 ± 10 kg and height = 1.81 ± 0.07 m) gave their written informed consent to participate in this study, with all procedures in agreement with the Declaration of Helsinki. This study met the ethical standards of the International Journal of Sports Medicine [17]. All were involved in regular physical activities, comprising strength-based resistance training with additional weights. All subjects were free of musculoskeletal pain or injury during the period of the study.

Design

Subjects participated to two sessions separated by 24 h to 72 h: the first session aimed to determine individual half-squat one-repetition maximum load and to familiarize subjects with loaded SJs; the second session consisted of assessing individual F-V relationships during loaded SJs.

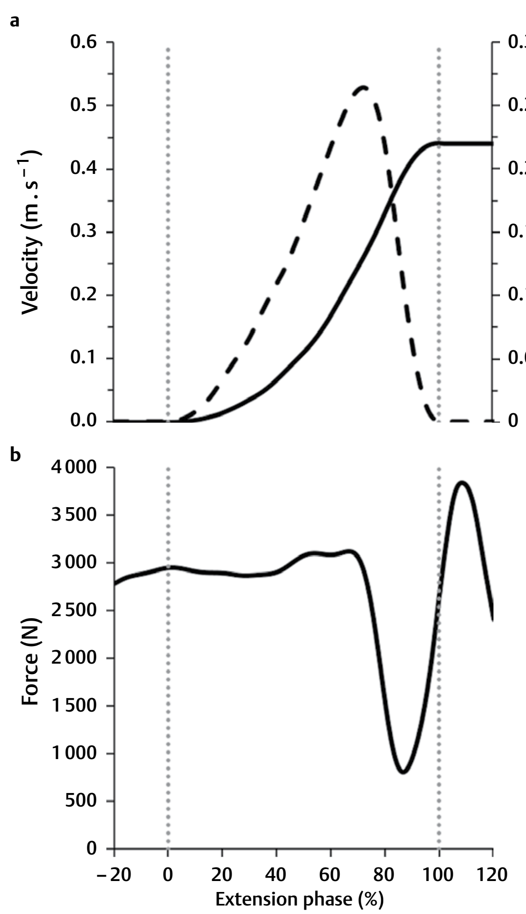
At arrival for the first session, body mass and leg length (corresponding to the distance between the iliac crest and toes in the fully extended leg) were measured. After ten minutes of warm-up composed of a pedaling exercise and light-load SJs, the preferential crouched starting position (associated with squat movement) was determined for each subject and the corresponding vertical distance between the ground and superior iliac crest was measured. Then, a passive reflective marker was placed on the skin on the anatomic landmark of the iliac crest. In the following procedures, the 1RM half-squat was assessed according to the reference method [24]. The determination protocol of the 1RM included specific warm-up weight-lifting exercises with different loads expressed as a percentage of estimated 1RM (8 to 10 repetitions at 30 %, 4 to 6 at 50 %, 2 to 4 at 70 % and 1 to 2 at 90 %; the estimation of 1RM was based on the subject's previous 1RM value obtained during the test routine or by multiplying body weight by 1.5 [26]). After 5 min of rest, subjects performed one trial with the 1RM load on a force plate: they were instructed to reach the previously defined crouched starting position (monitored using a vertical ruling gauge) and thereafter to maintain this position for 1 s to produce concentric force as quickly and aggressively as possible with maximum intent [26]. If they succeeded, they were asked to attempt a higher load, until their true 1RM load was reached.

The second session consisted of the identical warm-up procedures as the first session, followed by a selection of loaded SJs in six conditions (additional loads from 0 to 100 % of body weight). Each loading condition was performed twice and the highest jump was used to determine individual F-V relationship [31, 32]. For each trial, subjects stood still holding a barbell across their shoulders for additional-load conditions or with arms crossed on the torso for the unloaded condition. They initiated the SJ with a downward movement to reach their individual starting crouched position (measured and monitored as per in the first session). After maintaining this position for 2 s, they were asked to apply force as rapidly as possible concentrically and to jump for maximum height. Subjects were instructed to keep constant downward pressure on the barbell throughout the jump and keep their chest upright. They were also prompted to touch down on the ground in the same leg position as they took off: extended leg with foot plantar flexion. Countermovement was verbally forbidden and carefully checked. If these requirements were not met, the trial was repeated.

Methodology

During the first session, each 1RM squat trial was performed on a force plate (Kistler type 9281B, Winterthur, Switzerland, 1200 Hz) synchronized with an optoelectronic system (MaxPro advanced 3D auto-tracking, Innovision Systems Inc., Columbiaville, MI, USA) including 3 high-speed cameras (A640, Basler, Ahrensburg, Germany, 120 Hz). The force signal obtained from the force plate was filtered (low-pass 4th-order Butterworth) with a 15 Hz cutoff frequency. The position of the iliac crest reflective marker was measured instantaneously with the optoelectronic system, smoothed using a 50-ms moving average window and then derived over time to obtain the iliac crest velocity signal, which was smoothed using a 75-ms moving average window. Force (F_{1RM}) and velocity (V_{1RM}) signals were then averaged over the upward phase defined to begin when the lowest point of the crouched position was reached and finished when the iliac crest reached the highest position (▶ **Fig. 1a**). Note that the push-off phase was defined here as the entire range of lower limb extension [31, 32] in contrast with previous studies in which only the accelerated phase was considered [36, 37]. This is supported by the fact that (i) the F-V relationship refers to the maximal capacities of the lower limbs over an entire lower limb extension; (ii) during the end of the extension, the force production, even if lower than the total weight, contributes to the upward bar displacement; and (iii) the relative proportion of the accelerated phase depends on the amount of additional load, which could include the effect of force-length relationship (or range of motion) in the F-V relationship.

During the second session, the mean force (F_{SJ}) and velocity (V_{SJ}) developed during the push-off phase of each SJ were obtained with



▶ **Fig. 1** Vertical displacement (a, black line), velocity (a, black dash line) and force (b, black line) over time during the lower limb extension phase of a 1RM half-squat for a typical subject. The lower limb extension phase is delimited by the 0 % (i. e. the starting crouched position) and the 100 % (i. e. the highest point reach by the iliac crest) over the abscissa.

a previously validated computation method [14, 31, 32] using the following equations:

$$V_{SJ} = \sqrt{\frac{gh}{2}} \quad (1)$$

$$F_{SJ} = mg\left(\frac{h}{h_{po}} + 1\right) \quad (2)$$

where m is the body mass, g the gravitational acceleration (9.81 m.s^{-2}), h the jump height and h_{po}, the push-off distance. In this study, h was determined from fundamental laws of dynamic and aerial time [2], the latter being obtained using an infrared timing system (Optojumpnext, Microgate, Bolzano, Italy). Individual h_{po} values were determined as the difference between the extended lower-limb length with maximal foot plantar flexion (iliac crest-toe distance) and the vertical distance between the iliac crest and ground in the starting position (both measured in the first session). For each subject, F_{SJ} and V_{SJ} values obtained from different SJ conditions were used to determine the F-V relationship in SJ (F-V_{SJ}), from which the theoretical maximal force and velocity were extrapolated ($F0_{SJ}$ and $V0_{SJ}$). Adding the point corresponding to the 1RM condition (based on F_{1RM} and V_{1RM} values) to the previous F-V_{SJ} relationship gave the F-V_{1RM} relationship.

Simple computations to determine force and velocity during 1RM squat

During a 1RM squat, the vertical movement velocity being null from the initial crouched position to the final stand-up position, the mean acceleration during the push is null. Based on the fundamental law of dynamics, the mean force developed during the lower limb extension (F) can be reasonably estimated knowing the total weight of the system:

$$F = (m + m_{1RM})g \quad (3)$$

with m_{1RM} the mass of the 1RM additional load.

The mean extension velocity of the lower limbs (V) can be computed as:

$$V = \frac{d}{t} \quad (4)$$

with d the displacement of the hip during the lower limb extension (measured here as the vertical displacement of the marker positioned on the iliac crest) and t the duration of the lower limb extension. These variables were obtained here using laboratory devices to test the validity of the simple computations rather than the validity of the devices themselves, in the knowledge that they can be easily obtained outside of the laboratory (see discussion section for further details).

Statistical analysis

All data are presented as mean ± standard deviation (SD). The alignment of 1RM point with the F-V_{SJ} relationship was first tested with the comparison of the goodness of fit between F-V_{SJ} and F-V_{1RM} relationships through the comparison for each individual of residual variance of both regressions using a Fisher's F-test. Also, the alignment of the 1RM point with the F-V_{SJ} relationship was quantified by computing the residual between the 1RM point and the F-V_{SJ} curve (difference between F_{1RM} and the force value on F-V_{SJ} curve at V_{1RM}), and compared to zero using a paired sample t-test. To situate the 1RM point on the force-axis of the F-V_{SJ} relationship, the difference between $F0_{SJ}$ and F_{1RM} and the difference between F_{1RM} and the mean force developed during the highest loaded SJ condition were calculated and tested with t-test for paired sample. To situate the 1RM point on the velocity-axis of the F-V relationship, V_{1RM} values were expressed relative to V_{SJ} obtained during the SJ with the highest load (i. e., the lowest velocity values obtained on the F-V_{SJ} relationship). Then, the correlation between $F0_{SJ}$ and 1RM values was tested using the Pearson correlation coefficient. Mean and standard deviation of the differences (expressed in raw and standardized values), paired sample t-test and the Pearson coefficient correlation were performed to compare the force and velocity measured

▶ **Table 1** Mean ± SD of force and velocity values for one-repetition maximum squats and squat jumps.

	Squat Jump		1RM squat	Maximal theoretical values from F-V_{SJ} relationship (i. e., $F0_{SJ}$ and $V0_{SJ}$)
	Lowest loaded condition (without additional load)	Highest loaded condition (44.5 ± 4.6 % 1RM)		
Force (N)	1460 ± 159	1841 ± 177	2131 ± 215	2411 ± 214
Velocity (m.s⁻¹)	1.3 ± 0.1	0.80 ± 0.07	0.22 ± 0.05	3.47 ± 0.97

Only lowest and highest loaded values of the six loaded squat jumps conditions are presented. 1RM: one-repetition maximum; *F-V_{SJ}*: Force-velocity relationship obtained in squat jump; *$F0_{SJ}$*: Maximal theoretical force obtained from the force-velocity relationship obtained in squat jump; *$V0_{SJ}$*: Maximal theoretical velocity obtained from the force-velocity relationship obtained in squat jump

during the 1RM squat using the proposed simple computation method to the force and velocity values obtained using the reference method. Each t-test was performed after checking distribution normality with the Shapiro-Wilk test. For all statistical analyses, a P value of 0.05 was accepted as the level of significance. The magnitude of the various differences computed for the above-mentioned analyses was assessed by standardization to the between-subject standard deviation. Hopkins' effect size (ES) scale was used to describe these magnitudes with < 0.2, 0.2 to < 0.6, 0.6 to < 1.2 and 1.2 to < 2.0 representing trivial, small, moderate and large effect, respectively [18].

Results

All F-V_{SJ} and F-V_{1RM} relationships were very highly and significantly fitted by linear regressions (r^2 = 0.95 to 1; all P < 0.01). The six additional loads for SJ conditions represented 0 %, 13.5 ± 1.8 %, 35.1 ± 5.8 %, 53.1 ± 11.2 %, 67.1 ± 10 %, 81.6 ± 12.3 % of body weight and 0 %, 7.4 ± 0.9 %, 19.1 ± 1.9 %, 28.7 ± 4.1 %, 36.6 ± 4 %, 44.5 ± 4.6 % of the 1RM load. Mean ± SD values of F_{SJ} and V_{SJ} corresponding to the highest (load of 44.5 ± 4.6 % 1RM) and lowest (without additional load) loaded conditions, F_{1RM} and V_{1RM} as well as $F0_{SJ}$ and $V0_{SJ}$ are presented in ▶ **Table 1**. The residual variances of the individual F-V_{SJ} relationship (106 to 1278 N^2, i. e., standard error of estimate from 10 to 36 N) and the F-V_{1RM} relationship (239 to 3070 N^2, i. e., standard error of estimate from 15 to 55 N) were not significantly different for nine subjects out of ten. The residual between the 1RM point and the F-V_{SJ} curve was − 100 ± 110 N (− 5 ± 5 %, ES = 0.43) and significantly different from zero (P = 0.018). F_{1RM} values were 2131 ± 215 N, which was significantly lower than $F0_{SJ}$ (P < 0.001), the difference being − 263 ± 131 N (− 10.9 ± 5.2 %, ES = 0.82), and F_{1RM} was significantly higher than the force developed during the highest SJ loaded condition (P < 0.001), the difference being 290 ± 81 N (+ 15.8 ± 4.4 %, ES = 1.35). In addition, $F0_{SJ}$ was significantly correlated with 1RM (r = 0.78; P < 0.01). V_{1RM} values were 0.22 ± 0.05 m.s^{-1}, which corresponded to 29.6 ± 7.2 % of V_{SJ} obtained during the SJ with the highest load. The bias between force and velocity values obtained with the simple computation method and the reference method during the 1RM squat were − 50.4 ± 43.3 N and − 0.002 ± 0.002 m.s^{-1}, respectively (all P = 0.005). Expressed as a percentage of the mean of the values obtained for the reference method, these biases were − 2.3 ± 1.9 % and − 0.81 ± 0.64 %, respectively. The effect size and Pearson correlation coefficient values for the differences between these parameters are presented in ▶ **Table 2**.

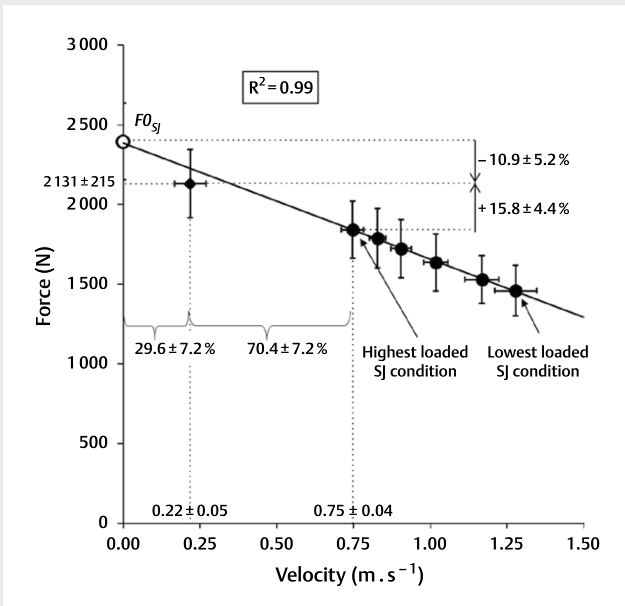
Discussion

The main findings of this study were, as hypothesized, that the 1RM point can be considered as aligned with the F-V relationship (i. e., no significant difference of goodness of fit with or without the 1RM point), even if it was positioned slightly under the curve (− 5 ± 5 %). The 1RM point was situated closer to F0 than to the highest loaded SJ condition point: the velocity during the 1RM squat was at 30 ± 7 % of the minimal velocity obtained during the highest loaded SJ. The force developed during 1RM was approximately 11 ± 5 % lower than F0, but 16 ± 4 % higher than during the SJ performed with the highest load (load of 44.5 ± 4.6 % 1RM, ▶ **Fig. 2**). The simple computation method proposed to estimate force and velocity during a 1RM squat yielded values that were very similar to those obtained using the reference method with small and trivial, though significant, systematic and random errors.

The present results supported the fact that the 1RM point can be considered as aligned with points obtained from loaded and unloaded SJs, which confirmed our first hypothesis based on the fact that the 1RM squat is overall similar to SJ, the only difference being a higher load to move. Although t-test and the residual showed that the 1RM point was significantly under the F-V curve by ~5 % in the present study, the effect size indicated that this mean difference was small (ES = 0.43). This result brings additional support to the linearity of the F-V relationship during squat movement, at least on its high force-low velocity side. Indeed, despite the fact that the linearity of the inverse F-V relationship on lower limb extension is currently admitted [5, 21, 31, 35], this linearity is often challenged on the basis that the F-V relationship on mono-articular movement or on isolated muscle is curvilinear [13, 39] and also due to the restricted range of experimental points used to derive the full F-V spectrum [9, 21]. Concerning the high velocity-low force side of the F-V relationship, a previous study attempted to reach high velocities during squat movements using 'negative load' (0.7BW lifted), nevertheless obtaining values far from V0 [9]. In contrast, V0 is easily approached in sprint running or cycling in comparison to squat because these are cyclic movements with some lower limb extensions occurring at the end of the 5–6 s sprints with low resistive force and when the mass has been already accelerated [1, 8, 29, 34]. Further studies are required to explore the low force-high velocity side of the F-V relationship to bring the same kind of support to its linearity during lower limb extension in squat movement. The fact that the 1RM point was slightly below the curve of the F-V relationship in this study can be interpreted as a non-maximal effort against the present 1RM load and in turn an underestimation of the 1RM load, which can be confirmed by the mean dif-

▶ **Table 2** Mean ± SD of force and velocity values obtained from the simple computation method and the reference method during one-repetition maximum squats.

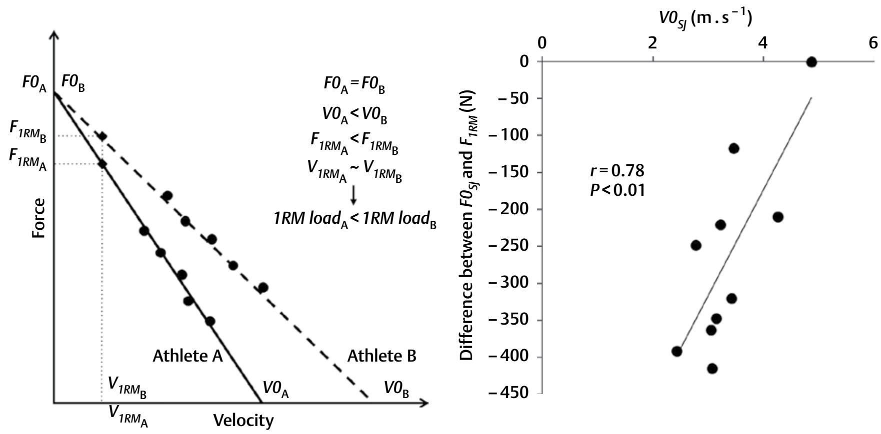
	Reference method	Simple computation method	Bias	T-test P-value	Effect size	Interpretation	Pearson correlation coefficient (P-value)
Force (N)	2131 ± 215	2181 ± 236	− 50.4 ± 43.3	0.005	0.23 ± 0.14	Small	0.99 (0.01)
Velocity ($m.s^{-1}$)	0.220 ± 0.051	0.222 ± 0.052	− 0.002 ± 0.002	0.005	0.04 ± 0.02	Trivial 1	(0.01)



▶ **Fig. 2** Force-velocity relationship obtained from loaded squat jumps (black points) and 1RM condition (black diamond). All symbols and values correspond to averaged data (± SD) across all subjects. The averaged horizontal position of the 1RM point relatively to the point of the highest loaded condition in squat jump (SJ) was underlined by the curly brackets and mean ± SD percentage values. The black pointers and mean ± SD percentage values depicts the averaged vertical position of the 1RM point relatively to $F0_{SJ}$ and the point of the highest loaded condition in squat jump.

ference in squat depth between squat jumps and the 1RM squats (0.13 ± 0.4 m). As expected from their F-V relationships, subjects' lower-limb neuromuscular systems could theoretically have developed a higher level of force against this load, and in turn accelerate it more, but they did not. Typically, weakness of other muscular chains, especially dorsal chains, may be the origin of this apprehension or incapacity to maximally accelerate the load. The 1RM underestimation could be explained by the task-induced apprehension with very high load that may have discouraged subjects from attempting a higher load. Also, this underestimation can be related to the limits associated with the incremental procedure of the direct method itself. In practice, when the additional load approaches the 1RM true value, high resolution in load increments (e. g., adding 1 or 2 kg) are required, which would inevitably increase the number of trials necessary to reach the true 1RM value. This would induce neuromuscular fatigue, and in turn diminish acute maximal strength capacity, and so prevent recording a true and accurate 1RM. All these potential causes could be reduced with subjects highly accustomed to high-load strength training or 1RM determination, which may not have been the case here, or if only the lower-limb muscle chains are involved in the movement (e. g., with the load carried at the hip). Finally, the small shift of the actual 1RM point under the F-V relationship could also partially be explained by some methodological limitations. The simple field method used to estimate lower-limb extension velocity during SJs is based on both center-of-mass dynamics and actual lower-limb extension range, whereas the instantaneous lower-limb extension velocity during the 1RM squat was derived here from the position-time signal of the iliac crest. Although a recent study has shown that the measurement of iliac crest velocity (with a linear transducer) instead of center-of-mass velocity (with a force plate) to estimate lower-limb extension velocity leads to small difference in measurements [14], this could have slightly influenced the 1RM point position compared to the F-V_{SJ} relationship. Also, the range of motion during the extension phase of the 1RM squat was lower (0.13 ± 0.4 m) than the range of motion during squat jumps due to less plantar flexion effort at the end of the extension phase.

The second aim of this study was to situate the 1RM point along the F-V relationship, notably regarding F0 and the point corresponding to the highest loaded SJ condition. In the population tested, the 1RM point was situated at ~30 % from F0 and ~70 % from the point corresponding to the SJ performed with the highest load on the velocity axis. On the force axis, the 1RM point was ~11 % below F0 and ~16 % above the highest force obtained during loaded SJs, and the effect size of the mean difference between F_{1RM} and F_{SJ} obtained during the SJ with the highest load was almost twofold higher than the effect size of the mean difference between F_{1RM} and $F0_{SJ}$. The 1RM point position relative to F0 is in line with the only previous study exploring these two variables, which reported that the 1RM was situated at ~16 % lower than F0 [22]. The slight discrepancy between these two average differences between F0 and F_{1RM} (11 % in this study and 16 % in the previous study) and the high variability (i. e., high standard deviation) in the difference between F0 and F_{1RM} underline the difficulty in accurately predicting 1RM from F0 based only on this difference. Although lower in magnitude, the force produced at 1RM was highly correlated with F0 ($r = 0.78$; $P < 0.01$), which is in accordance with previous studies reporting high correlations between these two parameters in the squat and bench press [9, 12, 22, 38]. The fact that the correlations obtained were not quasi-perfect confirms that 1RM and F0 are not exactly identical. Indeed, F0 corresponds to the theoretical maximal dynamic force that lower limbs could produce over an extension at null velocity. Even if this condition is purely theoretical, it is estimated from dynamic contractions and represents the limit towards which the lower-limb force production capacities tend. Contrastingly, the 1RM represents the dynamic maximal force that lower limbs can actually produce in practice over an extension, but with a non-negligible velocity [7, 19, 20]. The position of the 1RM



▶ **Fig. 3** The left panel depicts a schematic comparison of force-velocity relationship of two hypothetical athletes with the same force capacities (F0) but different velocity qualities (V0). Points correspond to squat jump conditions and diamonds represent the 1RM squat condition. The black line refers to the athlete A with a steeper F-V and the dash black line refers to the athlete B with the higher V0. The right panel presents the correlation between individual velocities qualities ($V0_{SJ}$) and the difference between force capacities ($F0_{SJ}$) and the mean force developed during the 1RM half-squat (F_{1RM}).

point along the F-V relationship (and its difference with F0) suggests that 1RM performance is affected partly (even slightly) by velocity qualities, and so does not represent only pure force capacities. This could be illustrated (▶ **Fig. 3**, left panel) by considering two hypothetical individuals with similar theoretical maximal force capacities (F0) but different velocity qualities (V0), and thus different F-V profile, who would perform a 1RM squat at approximately the same velocity [15]. The individual with the more force-oriented (steeper) F-V profile, and thus the lower velocity qualities, would present a higher difference between the force developed during the 1RM squat and F0. Consequently, this athlete would present a lower 1RM load despite a similar F0. This was supported in the present study by the significant positive correlation between individual $V0_{SJ}$ and the difference between $F0_{SJ}$ and F_{1RM} ($r = 0.78$; $P < 0.01$; ▶ **Fig. 3**, right panel): the lower V0, the higher the difference between F0 and the force developed during a 1RM. Finally, even if the 1RM still represents a good practical index of dynamic maximal strength, it cannot be associated with the purely maximal force capacities (F0). Otherwise, because F0 corresponds to the theoretical maximal force at null velocity, its relationship with the isometric maximal force was previously tested, but the two indexes have demonstrated no correlation [30]. This was explained by the fact that the force developed during the isometric contraction is measured at a fixed angle, whereas F0 is extrapolated from values measured on dynamic movements over a full range of extension. Overall, 1RM, F0 and isometric maximal force are three indexes commonly used to characterize maximal strength capacities, but they all represent quite different force production modalities.

When the underestimation of the 1RM is reduced (e. g., subjects accustomed to 1RM determination or to very high load strength training), it would be useful to add the 1RM point to F-V relationship analysis [19], notably because the 1RM determination is usually already included in testing routines in strength and conditioning. Indeed, the proximity of the 1RM point with F0 would reduce the extrapolation of the latter, and in turn improve the accuracy and the reliability of its determination. When 1RM is determined in practice, typically only load is considered due to a lack of availability of force and velocity data. That is why a simple computation method was proposed here to estimate force and velocity during a 1RM squat in the field. The pertinence of the values obtained with the proposed simple computations was first confirmed with high correlation results with the reference method ($r = 0.99$ – $P = 0.005$ and $r = 1$ – $P = 0.005$ for force and velocity parameters, respectively). Although all the values for the simple computations were significantly different from the reference method, the mean bias (−50.4 N and −0.002 $m.s^{-1}$), the small and trivial mean effect sizes (0.23–0.04), respectively, confirmed an acceptable accuracy of force and velocity parameters estimated. Furthermore, lower-limb extension velocity was obtained here with laboratory devices to validate the computation itself and not the devices. However, push-off time and distance (i. e., the difference between the hip height in stand-up and starting positions) could be easily obtained during a 1RM squat with a standard video-capable device (~30 Hz). Based on mean values observed in present study, the time resolution associated with a 30 Hz video frame rate would result in an error in velocity estimation of ~0.007 $m.s^{-1}$ (i. e., ~3 %). Consequently, mean force and velocity during a 1RM squat or squat can be easily estimated in the field by applying the simple computations method proposed. This could allow strength and conditioning coaches to add the 1RM point to the F-V relationship analysis without any laboratory devices, and in turn improve the reliability of the associated variables (notably F0).

Conclusion

In the present study, the "one-repetition maximum" (1RM) point was shown to be aligned with the force-velocity (F-V) relationship obtained in the squat jump (SJ), even if slightly situated here below the curve. In comparison to the other points of the F-V relationship, the 1RM point force value was ~16 % higher than for the highest loaded SJ point but ~11 % lower than F0. The velocity of the 1RM point represented ~30 % of the velocity reached during the highest-load SJ condition. This supported the fact that F0 and 1RM, which both represent dynamic maximal strength capacities, are not exactly similar, though highly correlated. Moreover, the distinction between the 1RM point and the highest loaded SJ point and its proximity with F0 suggest that adding the 1RM point to the F-V relationship analysis would be useful to improve the reliability of the determination of the force-velocity mechanical variables. The simple computation method proposed allows sport practitioners to accurately estimate force and velocity during a 1RM squat when the athletes are accustomed to heavy- load squat exercises. Overall, these findings bring additional support to the linearity of the F-V relationship in squat movement, at least when considering the force side.

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Conflict of Interest

We declare that we have no conflict of interest.

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