The version of record of this manuscript has been published and is available in European Journal of Sport Science 07/April/2020
http://www.tandfonline.com/10.1080/17461391.2020.1753816

Title: Comparison of linear, hyperbolic and double-hyperbolic models to assess the force-velocity relationship in multi-joint exercises

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Word count: 4214 (main text)

Abstract

This study assessed the validity of linear, hyperbolic and double-hyperbolic models to fit measured force-velocity (F-V) data in multi-joint exercises and the influence of muscle excitation on the F-V relationship. The force-joint angle and F-V relationships were assessed in 10 cross-training athletes and 14 recreationally resistance-trained subjects in the unilateral leg press (LP) and bilateral bench press (BP) exercises, respectively. A force plate and a linear encoder were installed to register external force and velocity, respectively. Muscle excitation was assessed by surface EMG recording of the quadriceps femoris, biceps femoris and gluteus maximus muscles during the unilateral LP. Linear, Hill's (hyperbolic) and Edman's (double-hyperbolic) equations were fitted to the measured F-V data and compared. Measured F-V data were best fitted by double-hyperbolic models in both exercises (p<0.05). F-V data deviated from the rectangular hyperbola above a breakpoint located at 90% of measured isometric force (F_0) and from the linearity at ≤45% of F_0 (both p<0.05). Hyperbolic equations overestimated F_0 values by 13±11% and 6±6% in the LP and BP, respectively (p<0.05). No differences were found between muscle excitation levels below and above the breakpoint (p>0.05). Large associations between variables obtained from linear and double-hyperbolic models were noted for F_0, maximum muscle power, and velocity between 25-100% of F_0 (r=0.70-0.99; all p<0.05). The F-V relationship in multi-joint exercises was double-hyperbolic, which was unrelated with lower muscle excitation levels. However, linear models may be valid to assess F_0, maximal muscle power and velocity between 25-100% of F_0.

Keywords: torque-velocity; muscle power; muscle mechanics; maximal unloaded velocity; biphasic force-velocity; velocity-based training.

1. Introduction

The evaluation of the force-velocity (F-V) relationship in different populations has extended widespread in recent years due to its functional significance (1-5). However, great discrepancies among studies exist in terms of the equation used during F-V profiling (6). According to the F-V relationship, the slower a muscle shortens the greater the force it can generate and *vice versa* (6).

The relation between force and velocity has been most frequently fitted to a rectangular hyperbola (7). Hill's equation has been considered a reference equation in different muscle preparations and during *in situ* conditions in humans. However, several studies found deviations from Hill's hyperbolic function in the high-force/low-velocity region of the F-V relationship (6). Measured isometric force (F_0) values in muscle preparations were 20-32% lower than those predicted by Hill's rectangular hyperbola (8, 9). Consequently, an alternative F-V – double-hyperbolic – equation that considered the biphasic nature of the F-V relation and fitted more adequately to the high-force/low-velocity region of the F-V relationship was proposed (10).

On the other hand, recent studies investigating the F-V relationship in humans during multi-joint exercises have reported that the F-V relationship follows a strict linear pattern (11-14). The linearity of the F-V relationship presents some practical advantages, since it can be assessed by collecting a few F-V data (15-17) while providing relevant information that can help optimize physical performance (3) and fatigue monitoring (18). However, some studies have found that F-V data collected from multi-joint exercises deviate from the linearity at very low forces (19, 20) and the existence of a double-hyperbolic pattern has been suggested at very high forces (20). The existence of a possible central inhibitory mechanism (lower muscle excitation levels) at specific ranges of the F-V relationship might be behind these deviations (21), which deserves to be further investigated. Importantly, the misconception of the shape of the F-V relationship can lead to serious errors in the estimation of several parameters derived from linear equations, such as F_0, maximum muscle power (P_{max}) or maximal unloaded shortening velocity (V_0). Of note, there might exist differences in the shape of the F-V relationship between multi-joint lower and upper body exercises due to the influence that muscle architecture and fiber type distribution have on the F-V relationship and the substantial differences in these parameters that may exist between lower and upper body skeletal muscles (22, 23).

Thus, the main goals of the present investigation were to compare the ability of linear, hyperbolic and double-hyperbolic models to fit measured external F-V data from multi-joint lower and upper body exercises, and to assess the influence of muscle excitation levels of quadriceps femoris (QF), biceps femoris (BF) and gluteus maximus (GM) muscles on the F-V relation.

2. Material and methods

2.1 Subjects

Unilateral leg press (LP) assessment was conducted in 10 cross-training male athletes (age= 25.8±5.4 years; height= 1.77±0.04 m; body mass= 78.4±3.2 kg; maximum isometric force= 2831.3±299.0 N) competing at the regional and national levels with a resistance training background of 4.3±2.6 years (8.7±2.4 h per week during the last year). On the other hand, bilateral bench press (BP) assessment was conducted in 14 recreationally resistance-trained male subjects (age= 24.0±4.3; height= 1.74±0.06 m; body mass= 73.7±9.3 kg; maximum isometric force= 1682.1±269.2 N) with a resistance training background of 2.8±0.8 years (2.5±0.8 h per week during the last year). All the participants gave their written informed consent. The study was performed in accordance with the Helsinki Declaration and approved by the local ethical committees.

2.2 Experimental setting

Unilateral (left) leg extensions were performed on a LP machine (Selection MED, Technogym, Italy), while BP performance was measured on a Smith machine with no counterweight mechanism (Multipower Fitness Line, Peroga, Spain). A force plate (LP: Type 9286BA, Kistler, Switzerland; BP: T-Force System, Ergotech, Spain) and a linear encoder (LP: Linear encoder, Chronojump Bosco System, Spain; BP: T-Force System, Ergotech, Spain) were installed on the equipment to evaluate external force and velocity data, respectively. In the LP setting, the force plate was mounted on the feet platform of the apparatus and the linear encoder was attached to the weights lifted during the exercise. In the BP setting, the force plate was mounted under the bench where the participants lay down with their feet over the bench (specifically built to be used over the force plate) and the linear encoder was attached to the bar used during the exercise.

The position of the subjects was standardized and kept the same between repetitions in both exercises. Both knee and elbow joint angles during the isometric contractions were measured by video analysis (HD Pro Webcam C920 1080p, 30 Hz, Logitech, Switzerland) in the LP and BP exercises, respectively. Superficial anatomical markers were placed on the skin of the participants on the superior border of the greater trochanter, inferior border of the lateral condyle and inferior border of the lateral malleolus for the LP setting, and on the lateral border of the acromion, the lateral epicondyle and the midpoint between radial and ulnar styloids for the BP setting. The camera was placed at a suitable distance (1.5 m), height (0.75 m) and position to capture the plane of the movement executed in the LP and BP exercises (sagittal and transverse planes of the human body, respectively).

Bipolar surface electromyography (EMG) recordings (Desktop DTS, Noraxon, USA) were obtained from the rectus femoris, vastus lateralis, vastus medialis, BF and GM muscles during unilateral leg extensions only. After skin preparation, surface EMG electrodes (HEX Dual Electrodes, Noraxon, USA) were placed over each muscle belly according to the SENIAM recommendations (24).

2.3 Experimental protocol

2.3.1 Force-joint angle relationship

After a standardized warm-up (10-min of moderate cycling, 3×6 dynamic repetitions at a self-reported low load and 10 submaximal to maximal isometric contractions), the force-joint angle relationships were evaluated at five different knee joint angles (97.4±4.5°, 110.2±4.9°, 121.8±3.8°, 131.3±3.7° and 141.0±3.6°) and seven different elbow joint angles (39.6±6.7°, 58.7±6.6°, 77.3±8.0°, 100.8±8.0°, 127.4±8.6°, 141.9±8.6° and 179.0±3.0°) (full extension is 180°) based on the characteristics and available positions of the used apparatus. The joint angles were tested in a randomized order and 2 trials were performed at each joint angle. After the cue "ready, set, go!" the subjects were asked to perform a 4-s maximal isometric contraction while verbal encouragement was given. A 2-min resting period was allowed between isometric repetitions. When the difference in force between two attempts at the same joint angle was higher than 5%, a third maximal isometric contraction was performed. The highest force value exerted at each joint angle was considered for further analysis. Finally, after the assessment of the F-V relationship, the isometric force-joint angle relationships were evaluated again in order to account for possible fatigue effects at each joint angle (calculated as [value post – value pre] / value pre). None of the participants showed a fatigue ≥10% at any evaluated joint angle, and so all of them were included in the final analysis.

2.3.2 Force-velocity relationship

After the initial evaluation of the force-joint angle relationship, maximal concentric contractions were performed as fast and strongly as possible. In order to record dynamic F-V data as close as possible to the individual maximum isometric force (i.e. high-force/low-velocity region of the F-V relation), initial knee and elbow joint angles (117.0±4.9° and 127.4±8.6°, respectively) were set to be as close as possible to the joint angles that maximized isometric force outputs (131.3±3.7° and 141.9±8.6°, respectively). Note that starting from smaller joint angles (which exhibit lower isometric forces) would limit the lifting of sufficiently heavy loads and the assessment of the high-force/low-velocity region of the F-V relationship. Subsequently, maximal concentric repetitions were performed to full extension (180º), first against increasing loads from 140 kg in the LP and 80 kg in the BP (~60–80% of F_0) to one repetition maximum (1RM) (LP: 234.0±28.5 kg; BP: 149.4±21.2 kg), and second against decreasing loads from 140 kg to 2.5 kg in the LP and from 80 kg to 0.5 kg in the BP. We ensured the measurement of at least 3 different loads in a window of 20 kg below the 1RM in order to obtain an adequate representation of the high-force/low-velocity region of the F-V relationship. Two attempts (repetitions) per load were performed consecutively with 1 min (>0.5 $m \cdot s^{-1}$), 2 min (0.2–0.5 $m \cdot s^{-1}$) or 3 min (<0.2 $m \cdot s^{-1}$) of rest between attempts and loads depending on mean velocity values exerted under the imposed loads. Then, a third attempt (repetition) per load was performed in the reverse order (from 2.5 and 0.5 kg to 1RM in LP and BP, respectively) to check that the results were not influenced by the lifting order (Supplementary material).

2.4 Data processing

In the LP setting, external forces and EMG signals were captured at a sampling rate of 1,500 Hz. Force and EMG data were acquired and synchronized with the same software (MyoResearch 3.10, Noraxon, USA). Raw EMG signals were smoothed via root mean square calculation using a 100 ms sliding window. The EMG amplitudes from rectus femoris, vastus lateralis and vastus medialis muscles were averaged to obtain QF muscle excitation, since no differences existed between individual muscles and all of them contribute to knee extension through the patellar tendon. Velocity was obtained from the differentiation of the displacement measured by the linear encoder at a frequency of 1,019 Hz. An external custom-built trigger (USB-6501, National Instruments, USA) associated to specific software (LabView, National Instruments, USA) was used to synchronize force and EMG with velocity data. An electromechanical delay of 50 ms was considered when reporting EMG-related values (25). In the BP setting, external forces and velocities were acquired at 1,000 Hz and synchronized by the same software (T-Force System v.3.65.1, Ergotech, Spain). In both settings, peak force and its corresponding velocity value were recorded from each concentric repetition to obtain the F-V relationship. Among these peak force and velocity at peak force values, the ones yielding the highest power (force × velocity) for each displaced load were selected. Ultrasound studies have found that collecting peak forces is an adequate strategy to obtain F-V values at a similar muscle length (26, 27). Regarding the isometric recordings, the highest peak force across all the recorded repetitions was selected. Joint angles during the isometric repetitions were assessed from the video recordings by specialized software (Tracker 4.11.0, https://physlets.org/tracker/).

A semilog approach was used to evaluate the appearance of a breakpoint derived from the double-hyperbolic behavior of the F-V relationship (9, 10). This approach consists in plotting the measured force as a function of the log of velocity. The appearance of two distinct linear relationships denotes the biphasic behavior of the F-V relationship with the breakpoint located at the intersection of the two linear regressions. Consequently, Hill's equation (hyperbolic function; nonlinear least squares method) (7) was applied on the F-V data below the breakpoint:

$$(F + a)(V + b) = (F_0^* + a)b \qquad (1)$$

where *F* is the force produced at a certain velocity of shortening *V*, F_0^* is isometric force estimated by Hill's equation, and *a* and *b* are constants. The ratio a/F_0^* denoted the magnitude of the curvature of the relationship, with a higher value describing a lesser curvature. V_0 was calculated as the intercept of the velocity axis. Then, the whole F-V data were fitted using Edman's equation (double-hyperbolic function; nonlinear least squares method) (10):

$$V = \frac{(F_0^* - F)b}{F + a}\left(1 - \frac{1}{1 + e^{-k_1(F - k_2 F_0)}}\right) \qquad (2)$$

where the first term expresses the F-V relationship at low and intermediate forces and F_0^* is the isometric force that is predicted from the rectangular hyperbola derived below the breakpoint; and the second term modifies the F-V relationship at high forces/low velocities (above the breakpoint) with k_1 and k_2 as constants. The second term is essentially a 'correction term' that reduces *V* in the high-force/low-velocity region of the F-V relation (10). In addition, a linear regression model was fitted to F-V data located above 50% of F_0 to assess whether measured F-V data deviated from the linear equation below a certain level of force (12, 13):

$$F = S_{FV}\, V + F_0 \qquad (3)$$

where S_{FV} is the slope of the linear F-V relationship. P_{max}, optimal force (F_{opt}) and optimal velocity (V_{opt}) were also calculated from the different resulting equations. Finally, the coefficient of determination (R^2) and the standard error of the estimate (SEE) were used to assess the fitting of the different models to the measured F-V data. The F_0^*/F_0 ratio was calculated to evaluate the degree of departure of the measured force and velocity values from the rectangular hyperbola, with higher values denoting a greater deviation.

2.5 Statistical analyses

Standard descriptive statistics and paired sample t-tests were used to identify possible fatigue effects in the force-joint angle relationships after the concentric measurements. Repeated measures

ANOVA was used to compare EMG amplitude recorded from the QF, BF and GM muscles at different regions of the F-V relationship: low-force/high-velocity (0.0–0.5 F_0), medium-force/medium-velocity (from 0.5 F_0 to the breakpoint), and high-force/low-velocity (from the breakpoint to 1.0 F_0). Differences between the parameters (F_0, V_0, P_{max}, F_{opt}, V_{opt}, R^2 and SEE) derived from double-hyperbolic *vs.* hyperbolic and linear equations were also assessed with repeated measures ANOVA testing. Pairwise comparisons were performed using a Bonferroni correction for multiple comparisons. Pearson's correlations were used to evaluate the validity of F-V data obtained from linear regression models. Statistical analyses were performed using SPSS v20 (SPSS Inc., Chicago, Illinois), and the level of significance was set at α=0.05.

3. Results

There were no differences in the force-knee joint angle relationship obtained before and after the F-V measurements, except at 141.0±3.6°, where maximal isometric force values were reduced after the dynamic measurements (p=0.008) (Figure 1A). The average change (fatigue) observed across the different knee joint angles was –3.5±4.8% (–2.1±5.1%, –2.5±5.8%, –3.8±6.1%, –3.9±4.3% and –5.1±2.9% at ~100°, ~110°, ~120°, ~130° and ~140°, respectively). In regard to the force-elbow joint angle relationship, maximal isometric force was reduced at 77.3±8.0° (p=0.004) and 100.8±8.0° (p=0.048) after the dynamic measurements, with no differences observed for the other elbow joint angles (Figure 1B). The average change detected across the different elbow joint angles was –1.6±2.8% (–1.9±11.6%, –3.3±8.8%, –3.4±4.1%, –2.9±6.4%, 3.0±5.5%, 1.8±6.5% and 0.3±7.3% at ~40°, ~60°, ~80°, ~100°, ~130°, ~140° and ~180°, respectively).

3.1 Comparison between Hill's (hyperbolic) and Edman's (double-hyperbolic) equations.

The F-V relationship showed a double-hyperbolic behavior in accordance with Edman's equation. No significant differences existed between the parameters derived from the double-hyperbolic model and any of the measured F-V data (all $p>0.05$). A breakpoint was found at 0.90±0.03 F_0 and 0.05±0.02 V_0 for the LP exercise (Figure 1C) and at 0.90±0.04 F_0 and 0.06±0.03 V_0 for the BP exercise (Figure 1D), above which measured force data deviated downwards regarding the rectangular hyperbola. Therefore, no significant differences between hyperbolic and double-hyperbolic models existed below 0.90 F_0 in both exercises (all $p>0.05$). Individual R^2 values obtained from the double-hyperbolic equation were higher than those obtained from the hyperbolic equation (LP: $p=0.026$; BP: $p=0.006$), while SEE values were lower using the double-hyperbolic compared with the hyperbolic equation (LP: $p=0.012$; BP: $p=0.010$) (Table 1). Additionally, isometric force values predicted by the hyperbolic equation were 12.5±11.1% and 5.9±6.1% higher than the measured isometric forces in the LP ($p=0.005$) and BP ($p=0.010$) exercises, respectively. A significant correlation was noted between F_0 values derived from both models (LP: r = 0.70, $p=0.023$; BP: r = 0.88, $p<0.001$). No significant differences were found in QF, BF and GM muscle excitation levels across the different regions of the F-V relation (Figure 2).

3.2 Comparison between linear and Edman's (double-hyperbolic) equations.

The measured F-V data deviated from the linearity below a certain level of force (Figure 1E and Figure 1F). There were no significant differences between measured F-V data and those estimated by linear models between 50 and 100% of F_0; however, differences were noted at 45% of F_0 (corresponding to 20 and 25% of V_0 in the LP and BP exercises, respectively) and below, with measured force data deviating above the linear equation in both exercises (LP: p = from 0.012 to <0.001, respectively; BP: p = from 0.041 to <0.001, respectively). Thus, individual R^2 values extracted from the double-hyperbolic equation were higher than those extracted from linear models (LP: $p<0.001$; BP: $p<0.001$), while SEE values were lower using double-hyperbolic compared with linear models (LP: $p=0.001$; BP: $p<0.001$) (Table 1). No significant differences existed regarding F_0 values, while V_0 and P_{max} values were found to be lower when obtained from a linear compared with a double-hyperbolic model in the evaluated exercises (both $p<0.05$). P_{max} occurred at 34.5±5.0% of F_0 and 30.0±4.9% of V_0 in the LP, and at 37.6±4.9% of F_0 and 34.9±5.7% of V_0 in the BP according to double-hyperbolic models; whereas in linear models P_{max} occurred at 50% of both F_0 and V_0.

3.3 Association between variables obtained from linear and Edman's (double-hyperbolic) equations.

Associations between F-V variables obtained from linear and double-hyperbolic models in the LP were reported for F_0 (r=0.97; p<0.001), P_{max} (r=0.87; p=0.001), V_{opt} (r=0.63; p=0.049) and velocity between 15 and 100% of F_0 (r= 0.76 to 0.98; p = from 0.012 to <0.001, respectively), but not for F_{opt} (r= –0.30) and V_0 (r= –0.02) (both p>0.05). Regarding the BP exercise, associations between variables obtained from linear and double-hyperbolic models were reported for F_0 (r=0.95; p<0.001), P_{max} (r=0.91; p<0.001) and velocity between 15 and 100% of F_0 (r= 0.58 to 0.99; p = from 0.030 to <0.001, respectively), but not for V_0 (r=0.08), F_{opt} (r= –0.30) and V_{opt} (r= –0.45) (all p>0.05). V_0 values estimated with the double-hyperbolic equation were correlated with velocities obtained from linear models between 40 and 60% of F_0 (r = from 0.54 to 0.73; p = from 0.046 to 0.003, respectively) and with measured velocities at 55% of F_0 and below (r = from 0.71 to 0.90; p = from 0.005 to <0.001, respectively) only in the BP exercise. Importantly, a correlation between the curvature of the F-V relationship (a/F_0) and discrepancies between V_0 values obtained from linear and double-hyperbolic models was found (r=0.85; p<0.001) (Figure 3).

4. Discussion

The main findings of the present investigation were that measured external F-V data obtained from two multi-joint exercises: i) deviated from the Hill's hyperbolic F-V relation above 90% of F_0; ii) deviated from the linear F-V relation at 45% of F_0 and below; and iii) were best fitted by the

Edman's double-hyperbolic model. In addition, the biphasic shape of the F-V relationship during unilateral leg extensions was not associated with lower muscle excitation levels in the high-force/low-velocity region.

The double-hyperbolic F-V relationship was first noted by Edman and colleagues in isolated single muscle fibers (8, 10). The F-V data deviated from the rectangular hyperbola at forces above 0.78 F_0 and velocities below 0.11 V_0, with measured isometric force values being 17% lower than those predicted by Hill's equation (10). Subsequently, additional studies confirmed the double-hyperbolic F-V relationship in different muscle preparations (9, 28-30). Interestingly, the characteristics of cross-bridge kinetics in the high-force/low-velocity region of the F-V relationship were found to explain deviations of F-V data below the rectangular hyperbola (31, 32). Two previous studies on the F-V relationship during isokinetic knee extensions have specifically evaluated the high-force/low-velocity portion of the F-V relation obtained from external F-V data in humans (33, 34). Their F-V data, collected from both voluntary and electrically evoked muscle actions, might correspond very well with the existence of the double-hyperbolic relationship, although the authors did not evaluate the adequacy of double-hyperbolic models, which was accomplished by the present investigation. Our data support the notion that the F-V relationship deviates from the rectangular hyperbola in the high-force/low-velocity region and that it is unrelated with a neural inhibitory mechanism. The latter is supported by observations made during electrically evoked muscle contractions (33) and strengthens the hypothesis that decreased force per cross-bridge may be behind this deviation (6). Therefore, in our study the classical hyperbolic equation overestimated maximal isometric force by 13% and 6% in the LP and BP exercises, respectively. Nevertheless, the degree of departure from the rectangular hyperbola was found to vary substantially between subjects (F_0^*/F_0 ratio ranged between 0.98-1.35), which deserves further investigation to elucidate the mechanisms behind these inter-individual differences. In addition, further studies should evaluate the reliability of the F_0^*/F_0 ratio across different days.

A recent review work on the shape of the F-V relationship has suggested that the apparent linear F-V relationship noted in multi-joint exercises may be in fact a misconception resulting from the relatively narrow range of forces that is usually evaluated in human studies (6). Even during unloaded squat jumps force production can reach ~50% of maximum isometric force (35). A recent study tried to address this issue by assessing the F-V relationship in the squat and BP exercises using a wide range of loads (36). However, the authors failed to obtain force values below 40% of F_0, and thus their conclusions on the linearity of the F-V relationship cannot be conclusive. In the present study we succeeded at obtaining F-V data ranging from 35 to 92% of F_0 in the LP and from 18 to 97% of F_0 in the BP exercises, and demonstrated that the F-V relationship behaves as a double-hyperbolic function also in multi-joint exercises. Accordingly, the linear F-V relationship fitted exceptionally the measured F-V data between 45-100% of F_0, but significant differences were observed out of this range and also regarding P_{max}, F_{opt} and V_{opt} values. The linearity of the F-V relationship in that range of forces would be facilitated by the deviations from the rectangular hyperbola noted at high forces (i.e. by the double-hyperbolic pattern).

Muscle power is an important determinant of physical performance in both young (37) and older adults (38) that depends on both force and velocity. Upon optimal excitation, force produced at high contraction velocities and V_0 are associated with the proportion and relative area of type II muscle fibers, while force produced at lower contraction velocities and F_0 are more influenced by other factors such as muscle physiological cross-sectional area (39, 40). Skeletal muscle architecture characteristics can also modulate substantially the F-V relationship (22). Therefore proper F-V testing and equation fitting can yield highly relevant data on the neuromuscular strengths and weaknesses of athletes or subjects from clinical populations that can be used to develop interventions targeting specific features by imposing specific stimuli. Numerous studies have recently used linear modelling to obtain F-V-derived variables to categorize subjects into different groups (2, 5) or to compare athletes with different fitness levels (41). However, we found that linear models overestimated F_{opt} by 38-46%, and underestimated P_{max} by 9-12%, V_{opt} by 33-40% and V_0 by 55-75%. Fortunately, no differences were found between F_0 values obtained from linear and double-hyperbolic models, while moderate-to-large correlations were noted regarding P_{max} and velocities exerted at 15-100% of F_0. In contrast, no association was reported between V_0 obtained from linear and double-hyperbolic equations. This is likely due to differences in muscle recruitment between repetitions performed at moderate-to-high forces (corresponding to the linear portion of the F-V relationship) and at moderate-to-low forces (corresponding to the portion of the F-V relation that deviates from the linearity) (6). In addition, velocity measured at 55% of F_0 and below was correlated with V_0 only in the BP exercise probably because of the lower curvature of the F-V relationship compared with that noted for the LP exercise (a/F_0 = 0.52 vs. 0.27, respectively; p<0.01). Actually, a strong association was found between the curvature of the F-V relationship (a/F_0) and discrepancies in V_0 obtained from linear and double-hyperbolic models (r=0.91; p<0.001) (Figure 3). This fact points out that the higher the curvature of the F-V relationship the lower the relative force that should be measured to obtain faithful V_0 values, which in turn can differ substantially between subjects. In any case, one of the main limitations of the present study was that V_0 was not directly measured, which may require of the evaluation of partially assisted concentric muscle actions. Future studies should evaluate the validity of V_0 derived from double-hyperbolic models and provide further details on the range of forces that should be measured to capture the truly characteristics of the F-V relationship in humans during multi-joint exercises.

F-V profiling has become an attractive and useful strategy to assess the neuromuscular function in various groups of people ranging from pubertal (1) and young adult athletes (2-4) to older adults (5). Linear F-V modelling is relatively easy and fast, but its limitations had not been previously reported. Linear F-V equations can be applied to F-V data above 45% of F_0, but their validity below 45% of F_0 is limited. Double-hyperbolic models should be used to obtain more accurate information on the F-V relationship during multi-joint exercises, requiring longer testing and processing time though. Fortunately, no differences existed between F_0 values obtained from linear and double-hyperbolic models, and P_{max} and velocity exerted between 25-100% of F_0 derived from linear equations may be adequate to discriminate between subjects due to their strong correlation ($r > 0.70$) with actual P_{max} and velocity values. However, additional studies are needed to ascertain whether V_0 can be adequately estimated from double-hyperbolic models using a specific range of F-V data. Furthermore, F-V data were collected in this study over a partial range of movement, and thus the influence of the force-joint angle relationship and the history dependence of muscle should be considered when comparing our results with data collected at different ranges of movement. Finally, it is important to note that to register as accurately as possible ground reaction forces produced by the upper-limb muscles during the BP exercise, the subjects must place their feet over the bench and no other movement than that produced by the arms while pushing the bar upwards should be allowed during the experiments.

In conclusion, the relation between force and velocity during two multi-joint exercises followed a double-hyperbolic pattern and was unrelated with a lower muscle excitation level in the high-force/low-velocity region of the F-V relationship. F-V data deviated from the rectangular hyperbola above 90% of F_0 and from the linearity below 45% of F_0. However, F_0, P_{max} and velocity between 25-100% of F_0 obtained from linear modelling were strongly related with those obtained from double-hyperbolic equations, which suggests that these may still be highly valuable for physical performance monitoring.

Acknowledgements

We thank all the participants for their collaboration and involvement in the experiments.

Disclosure statement

The authors report no conflict of interest.

Funding

This work was supported by the Ministerio de Economía y Competitividad of the Spanish Government (MINECO/FEDER, EU) under Grants DEP2015-69386-R and BES-2016-077199; Biomedical Research Networking Center on Frailty and Healthy Aging (CIBERFES) and FEDER funds from the European Union under Grant CB16/10/00477; and Ministerio de Educación, Cultura y Deporte of the Spanish Government under Grant FPU014/05106.

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Table 1. Parameters obtained from linear, hyperbolic and double-hyperbolic models.

	Linear			Hyperbolic			Double-hyperbolic		
	Mean	±	SD	Mean	±	SD	Mean	±	SD
Leg press									
F_0 (N)	2851.5	±	268.1	3193.2	±	373.8**	2841.2	±	247.3
V_0 ($m \cdot s^{-1}$)	1.20	±	0.38**	3.39	±	0.66	3.39	±	0.66
P_{max} (W)	855.5	±	197.8**	971.2	±	181.5	971.2	±	181.5
F_{opt} (N)	1425.7	±	134.1**	975.7	±	133.3	975.7	±	133.3
V_{opt} ($m \cdot s^{-1}$)	0.60	±	0.19**	1.01	±	0.22	1.01	±	0.22
R^2	0.967	±	0.018**	0.990	±	0.009*	0.997	±	0.003
SEE ($m \cdot s^{-1}$)	0.034	±	0.013**	0.029	±	0.010*	0.019	±	0.008
Bench press									

F_0 (N)	1607.1 ± 254.7	1781.8 ± 346.8**	1639.9 ± 246.4
V_0 (m·s^{-1})	1.42 ± 0.28**	3.18 ± 1.38	3.18 ± 1.38
P_{max} (W)	570.9 ± 113.3**	626.1 ± 123.2	626.1 ± 123.2
F_{opt} (N)	803.6 ± 127.4**	582.2 ± 181.4	582.2 ± 181.4
V_{opt} (m·s^{-1})	0.71 ± 0.15**	1.06 ± 0.33	1.06 ± 0.33
R^2	0.947 ± 0.041**	0.996 ± 0.003*	0.998 ± 0.002
SEE (m·s^{-1})	0.087 ± 0.048**	0.030 ± 0.014*	0.020 ± 0.011

F_0: maximal isometric force; F_{opt}: optimal force; P_{max}: maximal muscle power; R^2: coefficient of determination; SD: standard deviation; SEE: standard error of the estimate; V_0: estimated maximal unloaded shortening velocity. V_{opt}: optimal velocity. Significant differences compared to the double-hyperbolic model are denoted by *($p<0.05$) and **($p<0.01$).

Figure 1. Force-joint angle and force-velocity (F-V) relationships obtained in the leg press (*panels on the left*) and bench press (*panels on the right*) exercises. (**a**) Force-knee and (**b**) force-elbow joint angle relationships prior to (*closed squares*) and after (*open squares*) the force-velocity measurements. (**c-f**) F-V relationships obtained from measured data (*open circles*). (**c** and **d**) Comparison of double-hyperbolic (mean ± SD [*black thick and thin lines*, respectively]; Edman's constants: LP: k^1 = 0.04±0.05 and k^2 = 0.95±0.02; BP: k^1 = 0.08±0.07 and k^2 = 0.97±0.03) and hyperbolic (mean ± SD [*grey thick and thin continuous lines*, respectively]; Hill's constants: LP: a = 866.8±492.3 and b = 0.90±0.47; BP: a = 924.6±647.3 and b = 1.41±0.93) models. Insets show the high-force/low-velocity portion of the F-V relationship. (**e** and **f**) Comparison of double-hyperbolic (*details above*) and linear (mean ± SD [*grey thick and thin dashed lines*, respectively]) models. Insets show the power-velocity relationship. *Angle-specific significant differences between maximal isometric force values prior to and after the dynamic measurements ($p<0.05$).

Figure 2. Comparison of muscle excitation levels recorded at different regions of the force-velocity (F-V) relationship. EMG data is presented relative to the high-force/low-velocity region of the force-velocity relationship (mean ± standard deviation). No differences were found across different portions of the F-V relationship (p>0.05). LF/HV: low-force/high-velocity region; MF/MV: medium-force/medium-velocity region; HF/LV: high-force/low-velocity region.

Figure 3. Differences between linear and double-hyperbolic models in terms of maximal isometric force (F_0), maximal unloaded shortening velocity (V_0) and maximal muscle power (P_{max}) for the unilateral leg press (*grey squares*) and bench press (*white circles*) exercises according to the curvature of the double-hyperbolic force-velocity relationship (a/F_0).