A Novel Two-Velocity Method for Elaborate Isokinetic Testing of Knee Extensors

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ABSTRACT

Single outcomes of standard isokinetic dynamometry tests do not discern between various muscle mechanical capacities. In this study, we aimed to (1) evaluate the shape and strength of the force-velocity relationship of knee extensors, as observed in isokinetic tests conducted at a wide range of angular velocities, and (2) explore the concurrent validity of a simple 2-velocity method. Thirteen physically active females were tested for both the peak and averaged knee extensor concentric force exerted at the angular velocities of 30°–240°/s recorded in the 90°–170° range of knee extension. The results revealed strong ($0.960 < R < 0.998$) linear force-velocity relationships that depict the maximum muscle force (i.e. the force-intercept), velocity (velocity-intercept), and power (their product). Moreover, the line drawn through only the 60° and 180°/s data (the '2-velocity method') revealed a high level of agreement with the force-velocity relationship obtained ($0.76 < R < 0.97$; all power < 0.001); while the force-intercept highly correlated ($0.68 < R < 0.84$; all power ≤ 0.01) with the directly measured isometric force. The 2-velocity method could therefore be developed into a standard method for isokinetic testing of mechanical capacities of knee extensors and, if supported by further research, other muscles. This brief and fatigue-free testing procedure could discern between muscle force, velocity, and power-producing capacities.

Introduction

Isokinetic dynamometry has often been recognized as the gold standard method for testing muscle mechanical capacities in healthy and physically active individuals, as well as in those recovering from injuries or other medical conditions [5, 15, 18]. However, similar to other functional tests that typically provide a single testing outcome [13], the interpretation of the results obtained from isokinetic dynamometry has always been somewhat challenging to interpret regarding particular mechanical properties of the tested muscles, such as their capacities to produce high levels of the force, velocity and power (i.e. the product of force and velocity) outputs. The authors have interpreted the recorded forces and torques rather arbitrarily, with regard to either the observed capacities of the tested muscles or the outcomes of the applied rehabilitation and training interventions [1, 6, 17]. Most of the authors at least implicitly agree that the tests conducted at low joint angular velocities or even isometric conditions predominantly reveal muscle 'strength' (i.e. force), while high angular velocities predominantly reveal muscle power [20, 25]. As a result, routine testing procedures often include several joint velocities, where 60°/s and 180°/s could be considered as the standard values [6, 20, 29]. However, it is also known that the maximum power is typically obtained at high angular velocities outside the standard testing ranges, while the maximum velocity is even higher [26]. As a consequence, despite some attempts [19], the isokinetic tests conducted at standard angular velocities neither discern between muscle force and power-producing capacities, nor allow for assessment of maximum velocity.

A solution of the problem discussed could be based on the muscle force-velocity relationship. Namely, although the typical force-velocity relationship of in vitro muscles should be curvilinear [10], the loaded functional multi-joint movements (e. g., jumping, running, cycling, lifting, throwing) typically display a strong and linear force-velocity relationship of the tested muscles [13, 27]. Parameters of such a relationship directly reveal the maximum force, velocity and power-producing capacities, theoretically, of the tested muscles, and the results are not only reliable but are also at least moderately valid [7, 13, 23]. Conversely, the force-velocity relationship of individual muscles tested by means of isokinetic dynamometry has often been considered to be curvilinear [4, 11, 24, 28]. However, most of the available data sets suggest that the 'curvilinearity' could mainly originate from the inclusion of the relatively high isometric force, while the ranges of angular velocities typically applied provide an approximately linear relationship between the measured force and velocity [4, 6, 8, 12, 24, 28]. Moreover, if the force-velocity relationship of individual muscle groups proves to be strong and approximately linear within a wide range of angular velocities, a similar approach to the recently proposed '2-load method' could be applied in routine testing [14, 30]. Specifically, it has been shown that the functional movements tested under only 2 distinctive loads could provide almost identical outcomes as the same movements tested under variety of external loads that inevitably require regression modeling, as well as a prolonged and fatigue-prone testing procedure. Since the standard isokinetic testing is typically conducted at prescribed joint angular velocities instead of under different external loads, the isokinetic test conducted at only 2 distinctive angular velocities could also differentiate between the force, velocity and power-producing capacities of the muscle tested.

To address both the presented problems and gaps in the literature, we tested the knee extensors' concentric force within a wide range of knee angular velocities. Note that the concentric contraction of knee extensors is the most frequently applied isokinetic test in the literature. The first aim of the study was to evaluate the shape and strength of the force-velocity relationships obtained. The second aim was to explore the concurrent validity of the 2-velocity method, based on the results obtained from only the typically applied 60 °/s and 180 °/s velocities, with respect to the standard linear regression method based on a wide range of the tested angular velocities. The results related to the first aim are expected to contribute to our understanding of the mechanical properties of knee extensors. The results related to the second aim, however, could encourage development of a simple '2-velocity method' for assessment of the force-velocity relationship, based on only 2 tested angular velocities, that could differentiate between the force, velocity and power-producing capacities of knee extensors and, possibly, other individual muscles.

Methods

Participants

Since we preferred a homogeneous group of participants, 13 healthy female students of physical education (age 21 ± 2 years, body mass 64 ± 7 kg, height 172 ± 7 cm; data presented as mean ± SD) were recruited through word of mouth and fliers posted at the School of Sport and Physical Education. All of them were physically active through their academic curriculum, which typically consisted of about 10 h a week of on average moderate physical activity. They were neither active athletes nor did they suffer from neurological diseases or recent injuries. The study was conducted in accordance with the Declaration of Helsinki and meets the ethical standards of the journal [9]. All participants signed informed consent forms approved by the institution's Ethics Committee.

Testing procedures

All measurements were performed in the university research laboratory, using a Kin-Com AP125 isokinetic dynamometer (Chatex Corp., Chattanooga, Tennessee, USA). Following a standardized 10-min warm-up consisting of 5 min of cycling and 5 min of callisthenic and dynamic stretching, the participants were seated in an upright position and fixed to the testing apparatus with the straps around the pelvis, thigh, and malleoli. The axis of rotation of the dynamometer was aligned with the lateral femoral condyle. The same experienced examiner supervised all of the tests. A detailed explanation and qualified demonstration were provided prior to each test along with a standardized verbal encouragement. Participants were asked to complete 2 to 3 submaximal practice repetitions prior to each test series.

Maximum muscle force was tested under both isokinetic and isometric conditions. The isometric test was performed first, and it later served for the assessment of the concurrent validity of the maximum force obtained from the force-intercept of the force-velocity regression model applied to the results of the isokinetic tests. The isometric test was conducted at an angle of 120 ° of knee extension (180 ° corresponds to full extension) [15]. Participants were instructed to extend the knee "as fast and as hard as possible" [2]. 2 maximal contractions were performed with a 30 s inter-contraction rest.

The range of motion was from 90 ° to 170 ° of knee extension for the isokinetic trials [3]. To obtain the force-velocity relationship from a wide range of force and velocity data, we conducted isokinetic tests at 5 angular velocities in the following order: 30, 60, 120, 180 and 240 °/s. Note that to extend the interval of the tested velocities, we added both a lower (i.e. 30 °/s) and higher velocity (240 °/s) to the most frequently applied range of 60–180 °/s of the knee angular velocities [6, 20, 29]. 2 experimental trials were performed as hard as possible at each velocity, and the trial with the highest peak force was used for further analysis. All subjects were able to reach the preset angular velocities including the highest ones. The rests were 30 s between the trials and 60 s between 2 consecutive velocities. A real-time visual feedback of the force-time curve was available during the strength assessment [2, 15]. Since the participants were without previous experience with isokinetic testing, a brief familiarization procedure was conducted prior to the data collection consisting of 5 trials performed at different testing velocities.

Data acquisition and analyses

The force-time curves were recorded at 500 Hz and low-pass filtered (5 Hz) using a second-order (zero-phase lag) Butterworth filter. In addition to both the peak and average muscle force assessed at each angular velocity, we also recorded the maximum isometric strength (F_{max}) within the same knee angle interval. Since force was directly recorded, in order to assess the force-velocity relationships, the selected angular velocity (in rad/s) was transformed into a linear velocity (m/s) by multiplying it with the length of individual lever arms. Force-velocity relationships were assessed both by fitting a linear regression through the force and velocity data obtained from all 5 angular velocities (linear regression method) and by drawing a line through the force and velocity data obtained only from the 60 and 180 °/s angular velocities (2-velocity method). The force-velocity relationships of both methods were extrapolated to determine the maximum force (F_0; force-intercept) and maximum velocity (V_0; velocity-intercept), as well as the slope of the relationship ($a = F_0/V_0$). Finally, the maximum power was calculated from the product of F_0 and V_0 ($P_0 = F_0 \times V_0/4$).

None of the sets of recorded forces deviated from normality (all $P > 0.05$; Kolmogorov-Smirnov test). Student's paired-sample t-test was used to test the differences between the same parameters obtained from the linear regression and 2-velocity method, while the relationship between them was tested by means of Pearson's correlations. The same correlations were used to assess the relationship between the 2-load method parameters F_0 and the directly measured maximum isometric force F_{max}. Standard errors of estimate were calculated for each individual set of data with respect to the values predicted by the corresponding linear regressions. Data were analyzed using SPSS 20.0 software (SPSS Inc. Chicago, IL, USA). Alpha was set at 0.05.

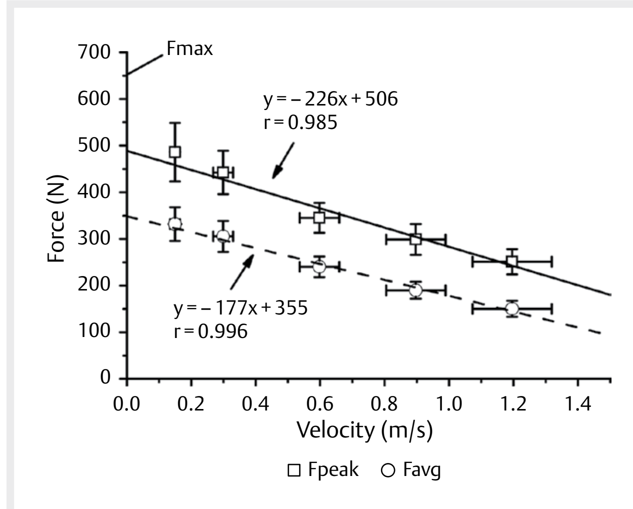
Results

▶ **Fig. 1** depicts both the peak and averaged values of force and velocity data averaged across the subjects. Although the angular velocities were fixed, somewhat different individual lever arms resulted in a certain variance of the calculated velocity. However, of utmost importance here is that although the data were obtained from a wide range of velocities, the linear regression method revealed exceptionally strong relationships for both sets of variables.

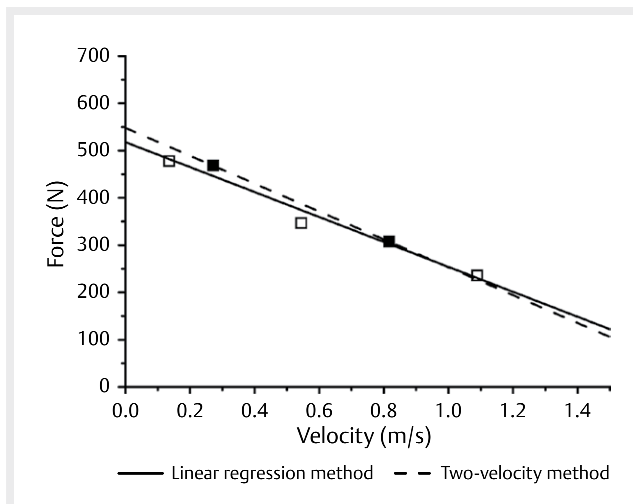
While ▶ **Fig. 1** shows the force-velocity relationships obtained from the data averaged across the subjects, the same relationships were also obtained from each individual set of data (see the solid line shown in ▶ **Fig. 2** as an example) by using the linear regression method. The median correlation coefficients were 0.978 (range 0.960–0.990) and 0.991 (0.982–0.998) for the peak and averaged force and velocity values, respectively, suggesting strong individual relationships. The same conclusion could be derived from the relatively low individual standard errors of estimate. They specifically revealed 23.1N (13.1–31.8N) for peak force and 11.2N (5.1–16.6N) for averaged force (data presented as mean and range). However, the force-velocity relationship was also obtained by applying the 2-velocity method. Simply stated, the relationship was obtained by drawing a line through the data obtained from only the 60 and 180 °/s values (see the dashed line in ▶ **Fig. 2**). Of utmost importance here is that the lines obtained by applying the linear regression and 2-velocity models almost overlap.

The comparison of the individual parameters of force-velocity relationships obtained by means of the individual linear regression method and the corresponding 2-velocity method is presented in ▶ **Fig. 3**. Of importance here is not only that there were no significant differences in their magnitudes (all $P > 43$; paired t-tests), but also that the magnitudes were strongly related ($0.76 < R < 0.97$; all $P < 0.001$; ▶ **Fig. 3**).

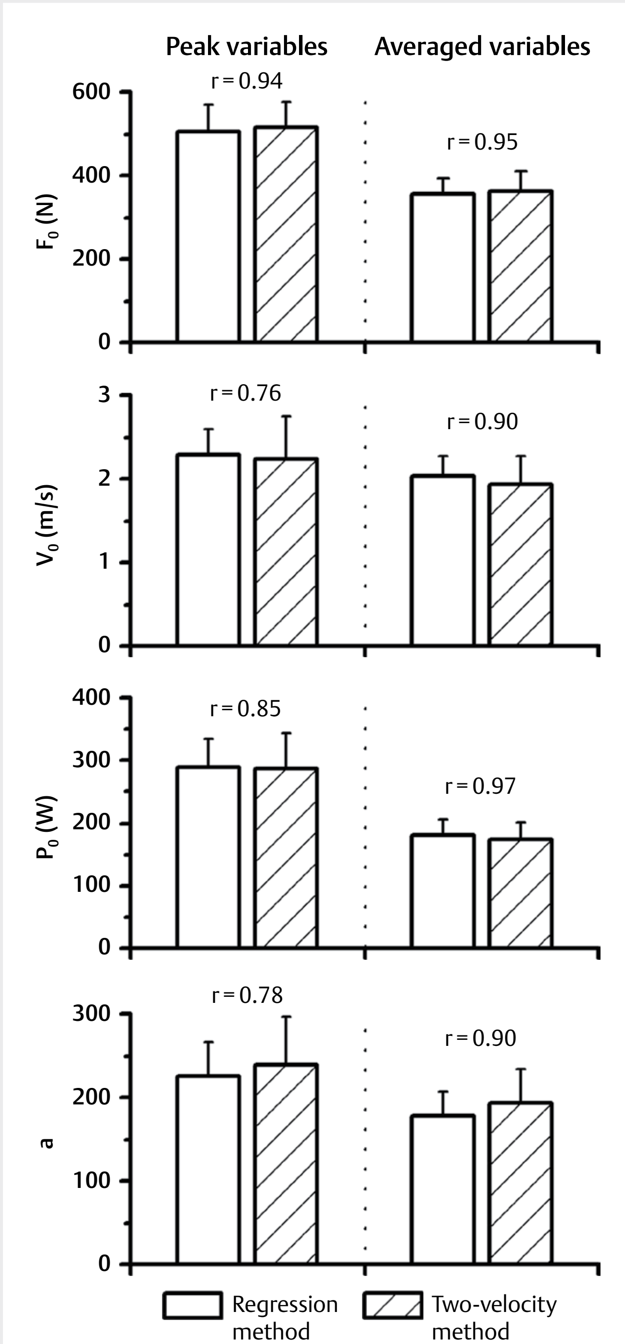
Finally, note that the recorded maximum isometric force $F_{max} = 647 \pm 114$N (the value indicated by arrow in ▶ **Fig. 1**) was not only well above the F_0 of the relationship observed from averaged, but also from the F_0 observed form the peak force and velocity data (see ▶ **Fig. 1** for illustration). Nevertheless, the correlation of F_{max} with the F_0 obtained from the linear regression method and from



▶ **Fig. 1** Averaged across the subject peak (squares; solid line) and averaged (circles; dashed line) knee extensor forces and velocities that served for the assessment of the force-velocity relationships (error bars indicate SD). F_{max} depicts the recorded maximum isometric force that was not included in the regression modeling.



▶ **Fig. 2** A representative set of individual data that illustrates a high level of correspondence between the outcomes of the linear regression method (solid line; all 5 data points included) and the 2-velocity method (dashed line; only the data indicated by solid squares included).



▶ **Fig. 3** The parameters of force-velocity relationships (data averaged across the subjects; means with SD error bars) obtained from the peak and averaged force and velocity data through the linear regression and 2-velocity method. The correlations between the outcomes of the 2 models are indicated in parentheses (all p < 0.001).

the 2-velocity method was 0.80 and 0.84 for the relationships obtained from the peak force, and 0.80 and 0.68 for the relationships obtained from the average force values, respectively (all P ≤ 0.01).

Discussion

The aims of the study were to evaluate the shape and strength of the force-velocity relationship of knee extensors tested by means of isokinetic dynamometry, as well as to explore the concurrent validity of a simple 2-velocity method applied on the same set of the data. In general, the first and rather novel finding was that the observed force-velocity relationships were strong and approximately linear. Consequently, we also found that the virtually identical force-velocity relationships could be also observed by using the '2-velocity method' based on testing knee extensors at only 2 standard angular velocities of 60 and 180 °/s.

Regarding the first aim, it should be noted that the tests were conducted within a wide range of velocities as compared to most of the standard testing procedures [6, 17]. Nevertheless, both sets of variables revealed strong and linear force-velocity relationships of the tested knee extensors. Although a visual inspection of the relationships observed from the peak force and velocity data indicate that the relationship could be slightly curvilinear, note that the linear regression method applied on either the averaged or individual force-velocity relationships revealed nearly perfect relationships. Therefore, the present study adds to the evidence that the force-velocity relationship of single-joint functional tasks could be approximately linear [13, 27]. However, it should be also noted that the directly recorded maximum isometric force F_{max} was well above the F_0 predicted by the applied linear regressions. Therefore, our findings are clearly in line with those reporting a relatively high level of F_{max} that motivated the authors to at least implicitly assume that the force-velocity relationship of individual muscle submitted to standard isokinetic testing could be generally curvilinear [4, 11, 24, 28]. Neither our study nor the studies of other authors that revealed the same observation provide the data that could help to elucidate the discussed phenomenon. Therefore, so far we can only speculate whether the observed difference between the predicted and recorded maximum isometric force originate either from the shape of force-velocity relationship, or the differences in the level of muscle activation, or the differences in knee angles that provide maximum isokinematic and isometric force, or from something else.

Regarding the second aim of the study, the data revealed a high level of agreement between the force-velocity relationship parameters obtained from the linear regression method and the 2-velocity method. Note also that the selected angular velocities of 60 and 180 °/s have been routinely applied in a number of standard isokinetic testing procedures [6, 20, 29]. Therefore, similar to the 2-load method applied on loaded functional movements [14], the 2-velocity method could also considerably simplify and shorten the assessment of the force-velocity relationship of individual muscles tested by means of isokinetic dynamometry. Note that the same outcomes can be observed through the force-velocity relationship (i.e. where force is directly measured, while the preselected angular velocity recalculated into linear velocity; the method applied in the present study) and by the torque-angular velocity relationship (the torque is directly measured and the angular velocity is preselected). Namely, the known lever arm allows for a simple conversion of force-velocity into torque-angular velocity relationship, and vice versa. The high level of agreement between the 2 methods is comparable to the level of agreement observed from 4 different functional tests when the force-velocity relationship of the tested muscles was observed from a number of loading conditions using a linear regression model and from just 2 loads, i.e. the '2-load method' [30]. Of particular interest could be that the 2-velocity method could also reveal valid indices of maximum force (i.e. F_0), velocity (V_0) and power (P_0)-producing capacities of knee extensors and possibly other muscles. The present data already suggest a high concurrent validity of F_0 with respect to the directly recorded F_{max}. Finally, note also that the relationship slope ($a = F_0/V_0$) also depicts the 'force-velocity profile' that needs to be optimized to maximize a particular movement performance [21, 22].

Within the present study we intentionally selected a homogeneous sample of participants and focused on a single but most frequently tested muscle. Therefore, regarding the directions of future research, of utmost importance could be conducting a similar evaluation on other muscles routinely tested by means of isokinetic dynamometry, as well as on diverse populations. If obtained, the strong linearity similar to the one observed in the present study could allow for a generalization of the present finding to the entire muscular system and, consequently, establishing the 2-velocity method as a the standard procedure for isokinetic testing. In addition, the reliability and concurrent validity of the force-velocity relationship parameters (and, consequently, of the 2-velocity method parameters) would certainly require further evaluation. A potential bias of the fixed order of velocities that has been often applied in routine testing procedures also deserves attention in future studies. Finally, a routine use of the 2-velocity method in the future would inevitably require evaluation of methodological elements of the applied procedures such as the standardization of the joint angles [16] and the selection of particular angular velocities.

We conclude that when isometric force is excluded, the force-velocity relationship of knee extensors tested by means of isokinetic dynamometry could be strong and linear even when it is tested within a wide range of knee angular velocities. That finding allows for a novel approach to the elaborate assessment of the mechanical capacities of knee extensors (i.e. the 2-velocity method) where only 2 trials performed at distinctive angular velocities could allow for discerning between the muscle force, velocity and power-producing capacities. Finally, if future research reveals a similar shape of the force-velocity relationship of other muscles, the 2-velocity method could be developed into a standard method for elaborate isokinetic testing of muscle mechanical properties for both clinical and non-clinical purposes.

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