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Force-velocity relationship of leg muscles assessed with motorized treadmill tests: two-velocity method

Running head: Force-velocity relationship of leg muscles

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Highlights

- Subjects exerted maximum horizontal force while walking on a motorized treadmill
- The resulting force-velocity relationship was linear, strong, and reliable
- The relationship parameters reveal muscle force, velocity, and strength capacities
- Almost identical outcomes were observed from only two velocities tested
- The 'two-velocity method' could be developed in a routine test of leg muscles

Abstract

Linear regression models applied on force (F) and velocity (V) data obtained from loaded multi-joint functional movement tasks have often been used to assess mechanical capacities of the tested muscles. The present study aimed to explore the properties of the F-V relationship of leg muscles exerting the maximum pulling F at a wide range of V on a standard motorized treadmill. Young and physically active male and female subjects (N=13+15) were tested on their maximum pulling F exerted horizontally while walking or running on a treadmill set to 8 different velocities (1.4-3.3 m/s). Both the individual (median R=0.935) and averaged across the subjects F-V relationships (R=0.994) proved to be approximately linear and exceptionally strong, while their parameters depicting the leg muscle capacities for producing maximum F, V, and power (P; proportional to the product of F and V) were highly reliable (0.84<ICC<0.97). In addition, the same F-V relationship parameters obtained from only the highest and lowest treadmill V (i.e., the 'two-velocity method') revealed a strong relationship (0.89<R<0.99), and there were no meaningful differences regarding the magnitudes of the same parameters obtained from all 8 V's of the treadmill. We conclude that the F-V relationship of leg muscles tested through a wide range of treadmill V could be strong, linear, and reliable. Moreover, the relatively quick and fatigue-free two-velocity method could provide reliable and ecologically valid indices of F, V, and P producing capacities of leg muscles and, therefore, should be considered for future routine testing.

Keywords: linear regression; two-velocity method; power; reliability; test

Abbreviations:

a, regression slope

CV, coefficient of variation

F, force

F_0, regression parameter (F-intercept) depicting maximum force output

ICC, intraclass correlation coefficient

P, power

P_0, regression parameter ($F_0 \cdot V_0/4$) depicting maximum power output

SEM, standard error of measurement

V, velocity

V_0, regression parameter (V-intercept) depicting maximum velocity output

Introduction

While the force-velocity (F-V) relationship of isolated muscles has been known to be hyperbolic [1], multi-joint functional tasks typically reveal strong and approximately linear F-V relationship patterns [2, 3]. Specifically, a manipulation of the external load provides a range of F and V data that allow for applying a linear regression model. Such results have been obtained from various maximum vertical jumps [4-8], cycling [9-11], leg press performed against various dynamometers and sledge devices [12-14], arm and upper body movements [6, 10, 11, 15], or consistently across variety of tasks [16]. The particular advantage of the linear over the hyperbolic F-V relationship is that the obtained parameters directly reveal the maximum F (i.e., F-intercept), V (V-intercept), power (P; proportional to their product) producing capacities of the tested muscles, while the regression slope depicts the balance of the muscles' F and V producing capacities [13]. Moreover, the same parameters typically proved to be highly reliable [4-8, 11, 15, 17] and at least moderately valid [4, 5, 9, 15]. As a consequence, a number of the authors have suggested that the standard tests typically performed under a single loading condition should be replaced by the F-V relationship modeling in both research and routine testing, since it provides outcomes of much higher informational value [2, 6, 10, 15, 17, 18].

Despite a large variety of functional tests that have been used to assess the F-V relationship of the involved muscles [2], a number of potentially important tests still remain underexplored. Of apparent interest for both the basic research and routine clinical testing should be the evaluation of the mechanical capacities of leg muscles performing a maximum effort during walking and running. So far, only P has been assessed from the F and V outputs recorded from single trials of maximum running typically performed on non-motorized treadmills [19, 20] or force plate data [21]. A similar treadmill allowed Jaskolska and co-workers [22] to obtain an approximately linear F-V relationship from multiple trials performed against different resistance F. However, most of the treadmills within the clinical and research settings are the motorized ones, while the tests conducted at a lower V could be more relevant for clinical studies than the previously evaluated running tests. Furthermore, non-motorized treadmills inevitably provide a variable V both between and within individual gait cycles, which poses a problem for the selection of F and V variables for further analyses. Finally, the running kinematic and kinetic patterns can considerably differ across different types of treadmills as well as ground conditions [23]. Therefore, both the pattern of the F-V relationship of leg muscles obtained from a wide range of V set by standard motorized treadmills and the basic properties of the relationship parameters still remain unexplored.

Of particular importance for future routine testing could be the shape of the observed F-V relationship. Namely, if the F-V relationship obtained from different treadmill velocities proved to be strong and approximately linear, it would allow for applying a simplified method for its assessment.

Specifically, similar to the 'two-load method' applied when testing other functional tasks that allow for manipulation of external loads [24, 25], a test conducted at only 2 distinctive treadmill V's (i.e., 'two-velocity method') could reveal the capacities of leg muscles to provide high F, V, and P outputs. Such an ecologically valid, highly informative, and a relatively quick and fatigue-free test would not be only of apparent importance for both the assessment of mechanical capacities of leg muscles, but also for the evaluation of various athletic training and rehabilitation interventions.

To address the discussed gaps in the literature, we designed a protocol for testing the F-V relationship of leg muscles from maximum pulling F exerted on a standard motorized treadmill within a wide range of the treadmill's V that covers the natural V of both walking and running. We specifically hypothesized that (1) the F-V relationship of the tested leg muscles would be strong and approximately linear, (2) the obtained relationship parameters depicting the maximum F, V, P, and slope (*a*) would be reliable, while (3) the magnitudes of the same parameters obtained from the simple two-velocity method would show a high level of agreement with their magnitudes obtained from the standard regression method applied on the entire set of F and V data. The hypothesized outcomes are expected to contribute to our understanding of mechanical properties of leg muscles. Moreover, the same outcomes would also motivate development of a routine and ecologically valid test of mechanical capacities of leg muscles, particularly those involved in gait. Namely, such a test conducted at lower velocities would be applicable not only to young and physically active populations, but also to elderly and frail individuals.

Methods

Subjects

Based on sample size estimates [26] conducted in previous studies of the F-V relationship obtained from loaded functional tasks (alpha 0.05 and power 0.80; [4, 15, 27]), we recruited 15 young male and 15 female students of physical education. They were highly physically active due to their standard academic curriculum, but none of them were active athletes. They had all been familiar with walking and running on motorized treadmills, while none of them reported either recent injuries or medical conditions that could compromise the tested performance. However, 2 male subjects were excluded from the sample because of not completing the testing protocol. They were informed regarding the potential risks associated with the applied testing protocol and also instructed to avoid any unusually strenuous activities over the course of the study. Informed consent was obtained from all individual participants included in the study. Both the experimental protocol and the informed consent were in accordance with the Declaration of Helsinki and approved by the Institutional Review Board.

Experimental protocol

The experimental protocol consisted of 3 sessions held between 8 and 11 a.m. The first session consisted of the collection of anthropometric data and 15 minutes of familiarization with the tested tasks. The second and third session (i.e., the test and retest) served for data collection. To minimize the potential confounding effects of muscle fatigue and soreness, the sessions were separated by at least 2 days of rest.

Physical characteristics

Body height was measured by a standard anthropometer with 0.1 cm accuracy. Body composition variables were measured with Biospace In-Body 720 (Seoul, Korea) using Direct Segmental Multi frequency–Bioelectrical Impedance Analysis (DSM–BIA method). Body mass index (BMI) was calculated from the subjects' body mass and height.

Recording the F-V relationship data

The testing was conducted on a motorized treadmill (HP Cosmos T170, Rome, Italy), using externally fixed strain-gauge dynamometer (CZL301, ALL4GYM, Serbia) connected to the subject wearing a wide and hard weightlifting belt (Figure 1). Prior to the data collection, the subjects completed a warm up procedure consisting of 10 minutes of both walking and running on the treadmill at a variety of treadmill velocities, followed by 5 min of callisthenic and dynamic stretching. The testing was conducted at the treadmill velocities set to 5, 6, 7, 8, 9, 10, 11 and 12 km/h (i.e., from 1.4 to 3.3 m/s) in a fully randomized sequence. The subjects were spontaneously walking or running on the treadmill depending on the velocity for about 10 s and, thereafter, instructed to exert the maximum pulling F against the dynamometer tether for 6 s, while the treadmill velocity was retained. According to a previous study (Spenser et al., 2008), 3 minutes of passive rest between the consecutive trials were enough to avoid the possible effects of fatigue. Verbal encouragement was systematically applied.

<Figure 1>

Note that the selected treadmill V's were based on the speed of transition that for similar population should be approximately in the middle of the tested interval (i.e., about 8 km/h; [28]). In addition, a pilot testing conducted prior to the experiment revealed problems with both inconsistent walking pattern and stability at a V higher than approximately 3.3 m/s, as well as long phases of double leg effort at the V below 1.4 m/s.

Data processing and analyses

Custom-designed software (LabVIEW, National Instruments, version 13.0, Austin, TX, USA) was used for the data recording and processing. F data were sampled at 200 Hz and filtered (10Hz lowpass recursive Butterworth filter). Out of the 6-second interval of exerting the maximum pulling F, the last 4 seconds of each trial were extracted, averaged, and used for further calculations.

F recorded at 8 treadmill V's were used to assess the F-V relationships both from the data averaged across the subjects and from the individual data. The main assessment approach was the 'regression method' based on the linear regression model applied on all 8 experimental points. In line with a number of previous studies [2], the regression $F(V) = F_0 - aV$ provided 4 parameters of apparent physiological meaning. Specifically, F_0 (i.e., the F-intercept) revealed the maximum F producing capacity of the tested muscles, V_0 (V-intercept) revealed their maximum velocity producing capacity, P_0 (equals $F_0 \cdot V_0/4$) depicted the maximum muscle power producing capacity, while the slope a (equals F_0/V_0) revealed the balance between the F and V producing capacities [13]. In addition to the regression method, a 'two-velocity method' was also applied to assess the same F-V relationship and its parameters. Specifically, the same F-V relationship was obtained as the line drawn through only the first and last point (i.e., the lowest and highest treadmill V).

Statistical analyses

The dependent variables of interest were the parameters of the obtained F-V relationships and the strength of the associated relationships. Descriptive statistics of the relationship parameters are presented as mean ± standard deviation (SD), while the correlation coefficients are presented through their medians and ranges. Normality of the data distribution was confirmed by the Shapiro–Wilks test. The test–retest reliability of the F-V parameters was assessed by the coefficients of variation (CV%), standard errors of measurement (SEM), and intra-class correlation coefficients (ICC) [29]. The smallest worthwhile changes were calculated according to Hopkins [30]. Pearson correlations were used to assess the strength of the relationships observed between the same F-V relationship parameters assessed by the regression method and the two-velocity method. Paired t-test and effect size were employed to assess the differences between the test and retest data, as well as between the same parameters observed by means of the 2 methods. All statistical analyses were performed using SPSS 21.0 (IBM Corporation) and Microsoft Office Excel 2007 (Microsoft Corporation, Redmond, WA, USA). Alpha was set at 0.05.

Results

The subjects' age was 21.5 ± 1.8 and 20.6 ± 1.8 years, body mass 77.7 ± 9.6 and 58.5 ± 6.2 kg, body height 182.1 ± 5.6 and 169.1 ± 5.8 cm, muscle mass 39.4 ± 4.7 and 26.4 ± 2.7 kg, body fat 10.8 ± 4.2 and 18.5 ± 3.4 %, and BMI 23.5 ± 2.70 and 20.5 ± 2.2, in males and females, respectively.

Figure 2 shows the F and V data of each group averaged across the subjects. As expected, males revealed markedly higher F at the same V than the females. The presented regression method provided the F-V relationship parameters F_0, V_0, P_0, and *a* to be 385 N, 8.16 m/s, 785 W, and 47.2 Ns/m in males, and 236 N, 6.70 m/s, 395 W, and 35.2 Ns/m in females, respectively. However, of utmost importance is that despite the relatively wide interval of the tested V, the regression method revealed almost perfect linear F-V relationships in both subject groups.

<Figure 2>

Table 1 shows the outcomes of the regression method applied on each individual set of the F and V data separately. As expected, the magnitude of individual F-V relationship parameters closely corresponds to those obtained from the data averaged across the subjects (see Figure 2), although minor differences remained due to the differences in the calculation methods used. There were no systematic differences between the trials (paired t-test; all $p > 0.1$ and $ES < 0.25$). The depicted correlation coefficients revealed strong individual F-V relationships. Finally, although the typical error evaluated by CV could be moderate on average, the reliability of the relationship parameters assessed by SEM and ICC (all ≥ 0.84) proved to be high. Comparison of ICC 95% CI suggests no differences in reliability between the 2 groups of subjects.

<Table 1>

Figure 3 illustrates the comparison of the regression method (F-V relationship observed from a linear regression applied on all 8 experimental points) with the 'two-velocity method' (F-V relationship observed from only the first and last point) in a representative male and female subject, while Table 2 shows a high level of agreement between them. Specifically, there were no differences in the magnitudes of the parameters observed by the 2 methods (paired t-test; all $p > 0.25$), all corresponding ES were below 0.1, while the correlations between their values were high (all $p < 0.001$).

<Figure 3>

<Table 2>

Discussion

To explore the F-V relationship of leg muscles, we tested the maximum pulling F exerted on a motorized treadmill set at a wide range of both the walking and running V. Regarding the stated hypotheses, the obtained results revealed (1) an exceptionally strong and linear F-V relationship of the tested muscles, (2) high reliability of the relationship parameters F_0, V_0, P_0, and *a*, while (3) a high level of agreement of their parameters suggest that the simple 'two-velocity method' could replace the standard regression method based on a number of the tested treadmill V.

Both the strength and shape of the observed F-V relationship are not only in line with the previous results obtained from leg muscles tested by partly different methodology [16, 22], but mainly in line with the findings observed from other functional movement tasks [see [2] for review]. In line with previous studies conducted on different functional tasks [4-8, 15, 17] are also the obtained high indices of reliability of the relationship parameters. One could even argue that the observed F-V relationships also provide valid indices of the mechanical capacities of the tested muscles. Namely, although the values of F_0 (388 N in males and 238 N females) could be somewhat below the maximum isometric pulling F that one leg can produce in horizontal direction, the magnitudes of V_0 (8.59 m/s and 6.86 m/s) closely correspond to maximum sprinting V of young and physically fit males and females, respectively, while P_0 (810 and 396 W) is similar to maximum P directly recorded in similar tests [19, 22]. Therefore, the present study adds to the evidence that not only the F-V of functional multi-joint tasks is strong and linear, but also that it provides reliable and valid indices of the F, V, and P producing capacities of the tested muscles.

Of particular importance could be the practical implications of both the strength and linearity of the observed F-V relationship. In line with other functional tasks [24], the presented results show that only two V tested can provide an almost identical F-V relationship as a number of tested V recorded for the purpose of regression modeling. Therefore, similar to the 'two-load method' applied to the tasks that allow manipulation of external loading [24], the 'two-velocity method' applied to the tested task can be employed both in research and routine testing. This would shorten and simplify the testing procedure and allows it to be fatigue-free, while still revealing an elaborate set of information regarding the mechanical properties of the tested muscles typical for F-V relationships observed from a number of either loads or V applied [2].

Taken together, the observed findings strongly speak in favor of the evaluated two-velocity method as a candidate for future routine testing of the mechanical capacities of leg muscles. Specifically, the motorized treadmills are typically available within clinical and athletic training facilities, while a reach set of information can be obtained from just 2 brief trials. Note that just one maximum sprinting trial performed either on a non-motorized treadmill [20] or on force plates [21] could also provide F-V relationship of leg muscles, although not as strong as that obtained by the regression methods applied in the present study. However, the treadmill sprinting could not only be a challenging task to perform even for young and healthy subjects, but also out of question for a number of clinical populations, as well as for elderly and frail individuals. Conversely, the exertion of the maximum pulling F while walking at treadmill set at a relatively low V, could be applied in virtually any subject population. Finally, the ecological validity of the evaluated test also needs to be taken into account. Namely, the treadmill walking more resembles the natural action of the tested muscles than the other often employed methods, such as the loaded cycling or the standard isokinetic tests of individual leg muscles.

Regarding the limitations of the present study and directions of further research, note that the applied methods provide only 2 independent parameters, while the remaining 2 can be thereafter calculated. Nevertheless, note that not only the muscle maximum F, V, and P producing capacities, but also the balance between F and V (i.e., the slope a; [13, 31]) have their distinctive physiological and functional meaning [2]. Note also, that the tested F exertion inevitably required an inclined body position and longer contact intervals with the belt than the natural walking and running at the same V. Therefore, similar to other functional movements [32, 33], the altered movement pattern could somewhat affect the obtained mechanical outputs. More research is apparently needed to optimize the testing protocol, such as the range of the tested velocities, number of experimental points needed, and the possible learning effects. Future studies could also explore the differences in F-V relationships between different populations, relationships between the same parameters obtained from the evaluated test and other tests of leg muscles, or the sensitivity of the F-V relationship when detecting the effects of various athletic training and rehabilitation interventions aimed to improve gait function. Finally, for the purpose of routine testing of clinical populations characterized with a lower level of muscle mechanical capacities, the F-V relationships obtained from lower V should also be evaluated.

Conclusions

The present results suggest that the F-V relationship of leg muscles tested at a motorized treadmill through the maximum pulling F at different V could be strong and linear, while its parameters could be highly reliable and, at least, partly valid. Moreover, a virtually identical relationship can be also obtained from only 2 distinctive treadmill V that allow for a relatively quick and fatigue-free testing procedure. Therefore, similar to the 'two-load method' applied to other movement tasks [24, 25], the 'two-velocity method' could be developed into a relatively quick and fatigue-free testing procedure that distinguishes among the F, V, and P producing capacities of the leg muscles while performing gait. Note that such a test would also be of high ecological validity since the contemporary routine evaluation of gait capacities are mainly based on the tests conducted either on cycling performed on stationary ergometers, or on isokinetic devices used to test individual muscle groups.

Conflicts of interest: none

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Figure captions

Fig. 1 Illustration of experimental conditions. Subject exerts the maximum horizontal pulling force while walking at a preset velocity on a motorized treadmill.

Fig. 2 Averaged across the subject pulling forces (F; means and SD error bars) and treadmill velocities (V) that served for the assessment of F–V relationships of leg muscles of males (squares) and females (circles). The regression lines are shown with the corresponding equations and correlation coefficients (R).

Fig. 3 Illustration of the F–V relationships of a representative male and female subject obtained by means of 2 methods. While the 'regression method' (solid line; equation and correlation coefficients shown) is based on all 8 experimental points, the 'two-velocity method' (dashed line; equations in parantheses) is determined by only the first and last experimental point.

Table 1. Magnitude and reliability of F-V relationship parameters obtained from 2 consecutive tests

		T1 Mean ± SD	T2 Mean ± SD	SEM	ICC (95% CI)	CV (%)	SWC
	F_0 (N)	385 ± 87	383 ± 70	2.33	0.97 (0.90-0.99)	6.4	16
	V_0 (ms^{-1})	8.7 ± 1.6	8.7 ± 1.6	0.11	0.93 (0.78-0.98)	11.1	0.3
M	P_{max} (W)	815 ± 140	820 ± 132	9.33	0.93 (0.77-0.98)	10.0	27
	α	47 ± 18	47 ± 17	0.86	0.95 (0.84-0.99)	15.7	3.5
	R	0.94 (0.89-0.98)	0.93 (0.88-0.98)				
	F_0 (N)	234 ± 53	241 ± 53	3.15	0.94 (0.84-0.98)	10.9	11
	V_0 (ms^{-1})	7.3 ± 1.4	6.9 ± 1.5	0.17	0.88 (0.65-0.96)	12.3	0.3
F	P_{max} (W)	415 ± 80	402 ± 57	10.96	0.84 (0.54-0.95)	14.0	14
	α	34 ± 13	37 ± 13	0.76	0.94 (0.80-0.98)	19.3	2.6
	R	0.93 (0.90-0.96)	0.94 (0.91-0.99)				

SEM, standard error of measurement; ICC, intraclass correlation coefficient with 95% CI; CV, coefficient of variation; SWC, smallest worthwhile change; ES, effect size; F_0, F-intercept; V_0, V-intercept; P_{max}, maximum power; α, slope; R, median correlation (range)

Table 2. Relationships between the parameters observed by 2 methods

		regression method mean ± SD	two-load method mean ± SD	R	ES
M	F_0 (N)	385 ± 88	388 ± 88	0.986	0.04
	V_0 (ms^{-1})	8.7 ± 1.6	8.7 ± 2.3	0.890	0.01
	P_{max} (W)	815 ± 140	814 ± 171	0.928	0.01
	α (Ns/m)	46.98 ± 18.45	49.23 ± 21.88	0.962	0.11
F	F_0 (N)	234 ± 53	237 ± 57	0.978	0.06
	V_0 (ms^{-1})	7.3 ± 1.4	7.3 ± 1.6	0.926	0.03
	P_{max} (W)	415 ± 80	414.2 ± 74	0.932	0.01
	α (Ns/m)	34.2 ± 13.2	35.5 ± 15.4	0.966	0.09

F_0, F-intercept; V_0, V-intercept; P_{max}, maximum power; *a*, slope; R, correlation coefficient; ES, effect size

Figure 1

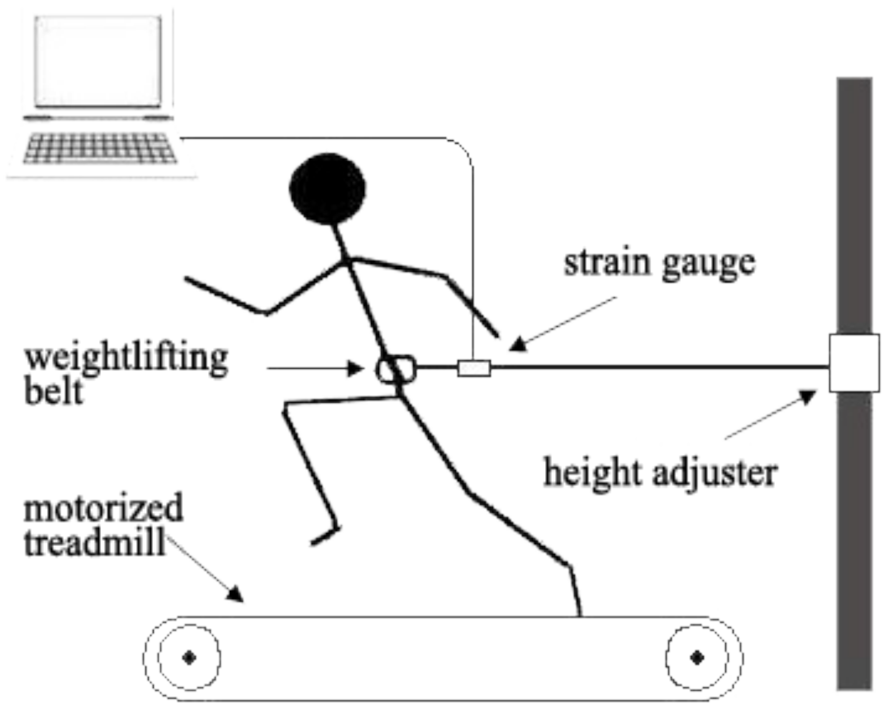
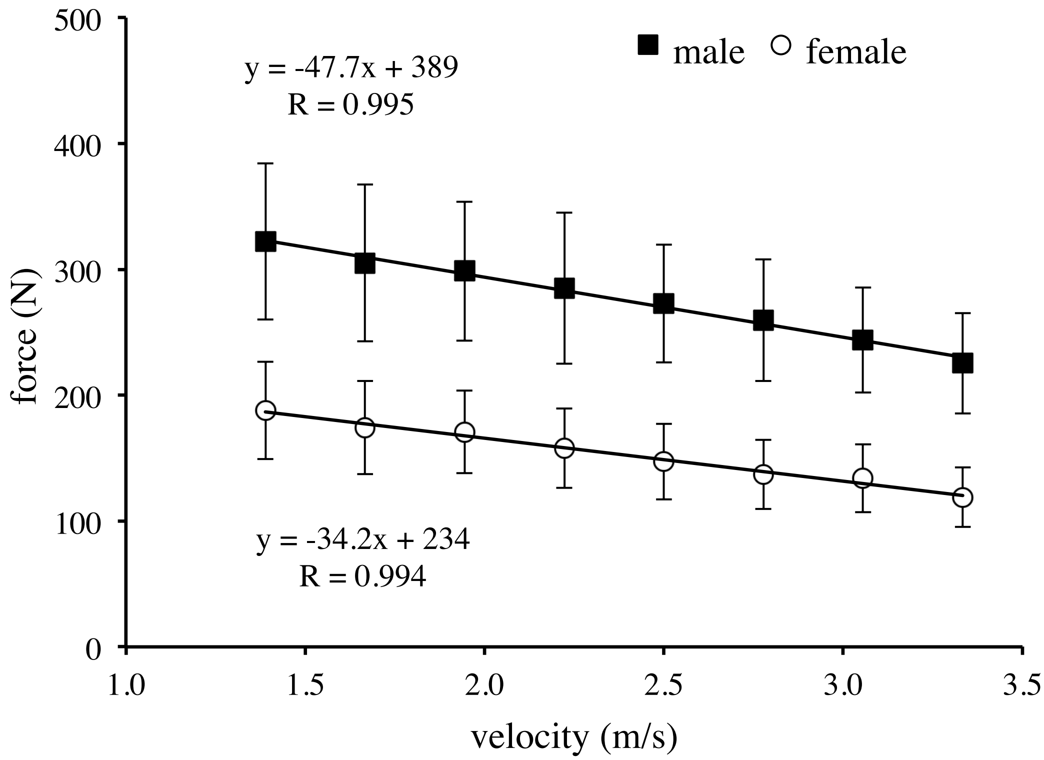
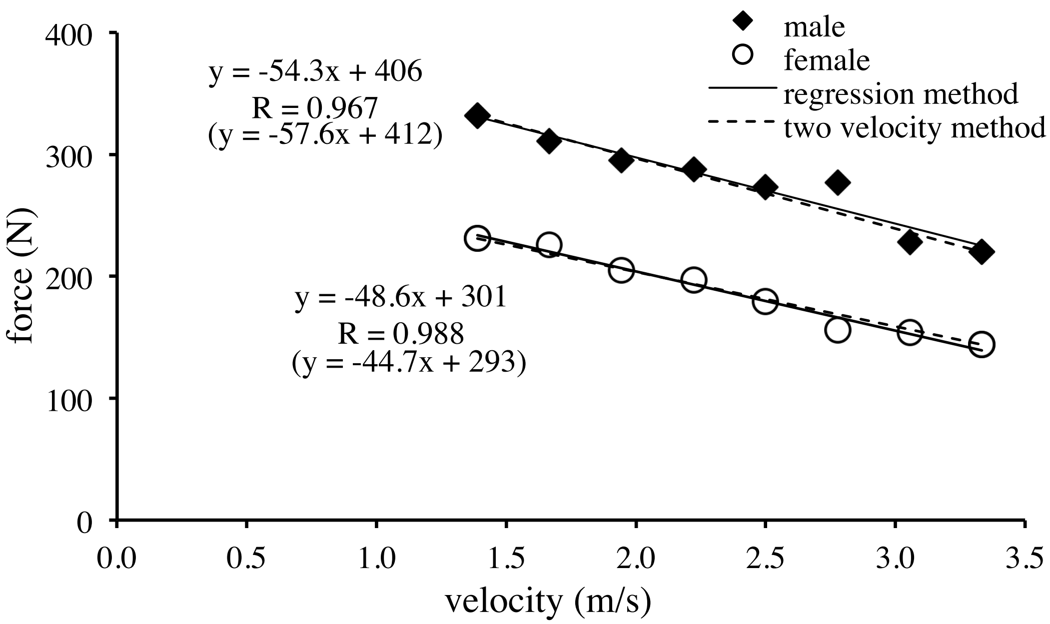

strain gauge
weightlifting belt
height adjuster
motorized treadmill

Figure 2



male
female
y = -47.7x + 389
R = 0.995
y = -34.2x + 234
R = 0.994
force (N)
velocity (m/s)
0
100
200
300
400
500
1.0
1.5
2.0
2.5
3.0
3.5

Figure 3



male
female
regression method
two velocity method
y = -54.3x + 406
R = 0.967
(y = -57.6x + 412)
y = -48.6x + 301
R = 0.988
(y = -44.7x + 293)
400
300
200
100
0
force (N)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
velocity (m/s)