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

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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.

1. 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

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

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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.

2. Methods

2.1. 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.

2.2. 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 min 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.

2.3. 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.

2.4. 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 (Fig. 1). Prior to the data collection, the subjects completed a warm up procedure consisting of 10 min 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 5–12 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 previous research, 3 min of passive rest between the consecutive trials were enough to avoid the possible effects of fatigue. Verbal encouragement was systematically applied.

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.

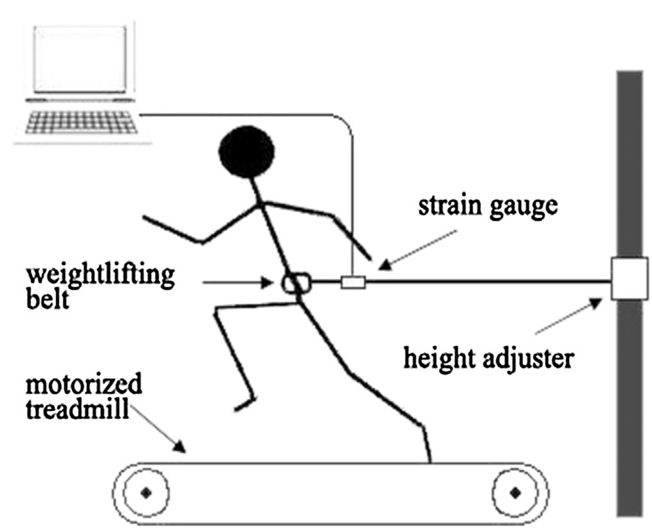

Fig. 1. Illustration of experimental conditions. Subject exerts the maximum horizontal pulling force while walking at a preset velocity on a motorized treadmill.