Gender Differences in the Relationship Between Quadriceps Work and Fatigue During High-Intensity Exercise

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ABSTRACT
The purpose of this study was to examine gender differences in peak quadriceps torque, the rate of torque decline, and the relationship between these 2 variables during high-intensity isokinetic exercise. Subjects for this study included 16 healthy men and 16 healthy women. Following a dynamic warm-up period, subjects performed 30 reciprocal, concentric maximal knee extension and flexion contractions at a preset angular velocity of 180 deg·sec⁻¹ on the Biodex System II Isokinetic Dynamometer. Values for quadriceps work (N·m) were calculated for each repetition between a windowed range of motion of 10° and 60° of flexion. Values for quadriceps work were then converted to a ratio of individual body mass (N·m·kg⁻¹). The rate of quadriceps fatigue was calculated as the decline in work output by the linear slope (β) across the 30 repetitions. This value was then assessed for gender differences with an independent t-test. The relationship between peak quadriceps work and the associated slope was examined by regression analysis for men and women, separately, and differences in these relationships were calculated using Fisher’s Z-transformation. The results demonstrated significantly higher peak quadriceps work and rate of fatigue (slope) in men as compared with women (p<0.05). The relationship between peak quadriceps work and the rate of fatigue was demonstrated to be significant in both sexes (men: r = 0.86; women: r = 0.69), and was statistically higher in men than in women. The findings from this study suggest that the physiological characteristics of quadriceps in men may be more conducive for high-intensity, short-term work output.

Key Words: isokinetic, concentric, slope, regression


Introduction
Injury to the lower extremity is a common and debilitating occurrence in many physically active men and women. However, competitive women athletes experience a significantly greater incidence of knee injuries than men. Specifically, the National Collegiate Athletic Association’s (NCAA) Surveillance System revealed that women athletes experienced a significantly greater number of knee injuries, including the anterior cruciate ligament (ACL), than men when matched by sport and exposure rate (4). Although many have speculated as to the underlying mechanisms of such injury patterns, few have demonstrated conclusive findings. The development of force, and subsequent fatigue, in the lower extremity may provide a plausible explanation for the disproportionate injury patterns, in addition to other structural differences such as genu recurvatum, greater quadriceps angle, and a narrow femoral notch width (21).

In the examination of muscular force and fatigue, numerous investigators demonstrated a distinctive pattern regarding gender differences (10–12, 16). With respect to the quadriceps muscles, Bell and Jacobs (1) showed that force and the decline of force over 25 maximal, isokinetic knee contractions was significantly higher in men than in women. Kanehisa et al. (16) who found that men (n = 27) generated significantly higher levels of quadriceps force than women (n = 36). These findings were also consistent when the force generated during isokinetic contractions at 180 deg·sec⁻¹ were calculated per unit of muscle cross-sectional area. These results suggest the notion that men demonstrate the capacity to generate greater muscular force, and as a consequence may develop a higher level of fatigue.
than women. In a series of studies, Hakkinen (10–12) investigated such a notion. During performance of a lower-extremity, closed kinetic chain activity, the squat lift, Hakkinen (11) found that men experienced a significantly greater amount of fatigue, and, hence, a longer recovery time than women. In a subsequent study, Hakkinen (12) also demonstrated that men displayed significantly higher levels of blood lactate than women during 10 sets of 10 repetitions of the squat exercise. In addition, men were shown to have greater reductions in maximal force generating capacity of the exercised muscles during the exercise than women. Based on these findings, it may be speculated that a relationship between the maximal force generating capacity of muscle and its rate of fatigue exists. Moreover, variations in this relationship that may exist between men and women may provide additional evidence regarding any discrepant injury patterns. It was, therefore, the purpose of this study to examine gender differences in peak quadriceps torque, the rate of torque decline, and the relationship between these 2 variables during high-intensity isokinetic exercise.

Materials and Methods

Subject Characteristics

Subjects for this study included 16 healthy men (age = 23.4 ± 3.7 years, height = 179.9 ± 5.1 cm, weight = 82.2 ± 12.1 kg) and 16 healthy women (age = 21.2 ± 1.8 years, height = 164.5 ± 6.1 cm, weight = 59.4 ± 7.2 kg). All subjects did not undertake lower-extremity resistance training for at least 6 months prior to the investigation. All subjects in this study were considered to be recreationally active (i.e., participated in activities such as jogging, cycling, and aerobic classes 2–3 days per week). Prior experience in resistance training beyond 6 months prior to participation or previous athletic endeavors were not ascertained. Individuals with a history of cardiovascular disease, diabetes, hypertension, and orthopaedic pathology or injury were excluded from participating in the study. Written informed consent was obtained in accordance with the Human Subjects Committee of the Biomedical Institutional Review Board of the University of Pittsburgh.

Isokinetic Torque Assessment

Isokinetic torque and fatigue was assessed on the Biodex System II Isokinetic Dynamometer (Biodex Medical, Inc., Shirley, NY). Subjects were placed in a comfortable, upright, seated position on the Biodex Dynamometer Accessory Chair and were secured using thigh, pelvic, and torso straps in order to minimize extraneous body movements. The lateral femoral epicondyle was used as the bony landmark for matching the axis of rotation of the knee joint with the axis of the dynamometer resistance adapter. Once the subject was placed in a position that allowed for a comfortable and unrestricted motion for knee extension and flexion from a position of 90° of flexion to terminal extension, the following measurements were taken: seat height, seat inclination, dynamometer head height, and resistance pad level. These measures were recorded and stored in the Biodex Advantage Software program version 4.0 (Biodex) in order to standardize the testing position for each individual subject. Gravity correction was obtained by measuring the torque exerted on the dynamometer resistance adapter with the knee in a relaxed state at terminal extension. Values for the isokinetic variable measured was automatically adjusted for gravity by the Biodex Advantage Software program. Calibration of the Biodex dynamometer was performed according to the specifications outlined by the manufacturer’s service manual. During the testing procedure, the cushion setting on the control panel for the ends of the range of motion were set to their lowest (hard) setting in order to reduce the effect of limb deceleration on the reciprocal motion (25). During the testing procedure, each subject was required to fold their arms across their chest and were given verbal encouragement as well as visual feedback from the Biodex computer monitor in an attempt to achieve a maximal effort level (13, 17, 19). The testing procedures were conducted by the same investigator for all of the subjects.

Reciprocal concentric isokinetic knee extension and flexion was assessed at a preset angular velocity of 180 deg·sec⁻¹. Prior to testing, each subject completed a dynamic warm-up period that consisted of submaximal cycling at 60 revolutions per minute for 5 minutes, followed by muscle stretching. Following 2–3 submaximal and 2–3 maximal familiarization repetitions, all subjects performed 30 maximal concentric repetitions. Quadriceps work is defined as the area under the isokinetic torque curve throughout a given range of motion (21). The values for quadriceps work were windowed between 10 and 60° of motion, in order to standardize the gender comparison in this study (9). Peak quadriceps work is defined as the single highest value attained during the 30 repetitions. These values were subsequently converted to a ratio of each subject’s body mass (N·m·kg⁻¹). The measurement of this variable has been consistently demonstrated to show high test-retest reliability (5, 9, 22).

Data Analysis

Gender differences in peak quadriceps work were computed with an independent t-test. The rate of quadriceps fatigue was determined by the decline in work output during the 30 repetitions. This calculation was performed via regression analysis to determine the individual linear slope (β) for each subject. Although a previous method to document fatigue, the fatigue index (percent of decline in torque output), has been used extensively during this protocol, studies have demonstrated low test-retest reliability for this.
measure (2, 22). Differences in the β-values, or the rate of fatigue, between men and women were then determined with an independent t-test. The relationships between peak quadriceps work and the associated slopes were examined via regression analysis for men and women separately. Differences in these relationships were then calculated by Fisher’s Z-transformation for testing differences between independent relationships (7). All tests of significance were carried out at a preset alpha level of \( p < 0.05 \).

**Results**

The results demonstrated that peak quadriceps work, corrected for body mass, was significantly higher in men than in women (\( t_{30} = 4.82, p < 0.05 \)). Peak quadriceps work was 1.35 ± 0.17 N·m·kg\(^{-1}\) for men, and 1.10 ± 0.11 N·m·kg\(^{-1}\) for women. Men also showed a significantly greater reduction than women in work output over 30 repetitions (\( t_{30} = 5.45, p < 0.05 \)), as demonstrated by the β values (men: \( β = -1.70 ± 0.47 \); women: \( β = -0.92 ± 0.32 \)). The relationships between peak quadriceps work and the rate of work decline (β) were found to be statistically significant in both men (\( r = 0.86, p < 0.05 \)) and women (\( r = 0.69, p < 0.05 \)). This relationship was found to be significantly higher in men (\( r^2 95\% \text{ confidence interval: } 0.57-0.95 \)) than in women (\( r^2 95\% \text{ confidence interval: } 0.295-0.885 \)). These relationships were also shown to fit a second order (quadratic) trend for both men (\( r^2 = 0.74, p < 0.05 \); see Figure 1) and women (\( r^2 = 0.51, p < 0.05 \); see Figure 2).

**Discussion**

The major findings of this study demonstrate that men generate significantly more concentric quadriceps torque (work) than women when corrected for body mass, which also appears to be related to a significantly higher rate of fatigue. It should be acknowledged that precise gender differences in fat-free mass were not addressed in this study. Specifically, the intent of the present investigation was to examine a rather simple method of torque normalization (body mass) that can be applied in clinical settings. The significantly greater relationship between peak quadriceps work and fatigue in men, as compared with women, suggests that the physiological characteristics of male skeletal muscle may be more conducive for high-intensity, short-term work output than female skeletal muscle.

Gender differences in the development of maximal concentric torque have been previously documented and have been attributed to a number of different factors. Perhaps the most obvious of these factors is the significantly greater amount of muscle mass in men as compared with women (14). In addition to significantly smaller values of total quadriceps muscle cross-sectional area (CSA) in women, it has been shown that these values are reflective of the larger CSA of the 3 main subtypes of muscle fibers in men (14, 16, 24). Although the present study used a very general method for normalizing quadriceps work (body mass), the results regarding peak torque relative to an anthropometric measure concur with those of Kancheisa et al. (16). Isometric torque values of the tibialis anterior muscle when corrected for the body mass index was also found to be 33% higher in men compared with women (3). It can be reasonably surmised that in addition to the morphological differences between men and women, the greater relative torque values may also be explained, in part, by neural drive. Although conclusive evidence has yet to be established, investigations have shown a marked difference in neuromuscular activation characteristics between men and wom-
en. Cioni et al. (3) found that the median power frequency of the electromyogram (EMG) was significantly lower in women during submaximal isometric contractions. It was subsequently suggested that this finding may be related to the smaller size of muscle fibers in women (14, 23). Alternatively, the earlier recruitment of more motor units over increases in rate coding was also proposed as an explanation for these findings (3, 26).

It can be assumed that the ability to sustain cyclic muscle contractions at a high relative force level is a product of the quality and quantity of neural drive and the metabolic profile of the muscle. The present study demonstrated that the ability to generate a high level of torque (peak work) was significantly related to a greater level of fatigue in both men and women. Moreover, the decline in quadriceps work over a brief period (30 seconds) was found to be significantly higher in men than women. Such findings were also demonstrated by Bell and Jacobs (1), who showed that men experienced a significantly greater reduction than women in isokinetic torque over 25 repetitions. Contrary to this, however, Kanehisa et al. (16) found that women experienced a greater rate of torque decline over 50 isokinetic quadriceps contractions than men when adjusting for the initial torque values through the analysis of covariance. Although statistically appropriate, the adjustment to the initial torque values removes the documented physiologic relationship between peak force generation and fatigue susceptibility. Furthermore, the longer duration of the exercise bout utilized by Kanehisa et al. (16), 50 repetitions, as compared with the present study may have contributed to their findings.

The ability to sustain neural drive to an exercising muscle is a critical component to performance. As was outlined, women have been shown to exhibit lower discharge frequencies than men at various levels of torque. During repeated squat exercise, Hakkinen (12) found that men experienced a significantly greater reduction than women in maximal isometric force (47.1 and 29.4%, respectively), and both groups showed significant decreases in maximal EMG. It was subsequently concluded that neuromuscular fatigue during repeated squat exercise was greater in men than women. Linnamo et al. (18) had similar findings, which showed that men appeared to experience significantly greater fatigue than women during bilateral knee extension exercises. In support of this contention, the glycolytic capacity of women has been shown to be lower than men (8), and the increase in blood and/or muscle lactate during short-term maximal contractions increases more in men than in women (6, 15). Although the present study did not examine specific neuromuscular or metabolic markers of fatigue, it was demonstrated that significantly greater relationships between peak quadriceps work and the rate of torque decline occurred in men as compared with women. However, it appears to be prudent to determine if this relationship can be modified by anaerobic or strength training, or if these characteristics are inherently gender-specific.

Practical Applications

The apparent fatigue-resistant characteristic of women's quadriceps muscles may suggest an enhanced ability to conduct prolonged exercise at high relative intensities. However, the reduced glycolytic capacity that has been previously demonstrated in women may prove to be a limiting factor for performing high absolute levels of work. In addition, women may also demonstrate a relatively lower level of neural drive to exercising muscle, thereby altering their ability for neuromuscular control of the lower extremity under fatiguing conditions. This fact coupled with the altering levels of fatigue during exercise may provide significant evidence that underlies injury risk factors for women. Although such a hypothesis has yet to be proven, the absolute and relative amount of quadriceps work that can be performed during maximal effort exercise demonstrates a significant gender discrepancy.

References