Gender differences in skeletal muscle fatigability are related to contraction type and EMG spectral compression

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Clark, Brian C., Todd M. Manini, Dwight J. Thé, Neil A. Doldo, and Lori L. Ploutz-Snyder. Gender differences in skeletal muscle fatigability are related to contraction type and EMG spectral compression. *J Appl Physiol* 94: 2263–2272, 2003. First published February 7, 2003; 10.1152/japplphysiol. 00926.2002.—The purposes of this study were *1*) to evaluate gender differences in back extensor endurance capacity during isometric and isotonic muscular contractions, *2*) to determine the relation between absolute load and endurance time, and *3*) to compare men [$n = 10$, age 22.4 ± 0.69 (SE) yr] and women ($n = 10$, age 21.7 ± 1.07 yr) in terms of neuromuscular activation patterns and median frequency (MF) shifts in the electromyogram (EMG) power spectrum of the lumbar and hip extensor muscles during fatiguing submaximal isometric trunk extension exercise. Subjects performed isotonic and isometric trunk extension exercise to muscular failure at 50% of maximum voluntary contraction force. Women exhibited a longer endurance time than men during the isometric task (146.0 ± 10.9 vs. 105.4 ± 7.9 s), but there was no difference in endurance performance during the isotonic exercise (24.3 ± 3.4 vs. 24.0 ± 2.8 repetitions). Absolute load was significantly related to isometric endurance time in the pooled sample ($R^2 = 0.34$) but not when men and women were analyzed separately ($R^2 = 0.05$ and 0.04, respectively). EMG data showed no differences in neuromuscular activation patterns; however, gender differences in MF shifts were observed. Women demonstrated a similar fatigability in the biceps femoris and lumbar extensors, whereas in men, the fatigability was more pronounced in the lumbar musculature than in the biceps femoris. Additionally, the MF of the lumbar extensors demonstrated a greater association with endurance time in men than in women ($R^2 = 0.45$ vs. 0.19). These findings suggest that gender differences in muscle fatigue are influenced by muscle contraction type and frequency shifts in the EMG signal but not by alterations in the synergistic activation patterns.

muscle activation; sex; back extensor muscles; electromyography; isometric; isotonic

NUMEROUS REPORTS SUGGEST that women have a greater muscular endurance capacity than men (18, 19, 24, 27, 41, 45, 50). The underlying physiological mechanisms causing this observed gender difference in muscle fatigability are not completely understood (22). Two of the most purported hypotheses to explain gender differences in endurance capacity are potential differences in muscle mass and neuromuscular activation patterns (22).

The hypothesis of gender differences in muscle mass mediating fatigue responses during muscular contraction has gained much popularity (22). This hypothesis framework is based on women having less muscle mass than men and, with the assumption of a similar specific tension, generating lower absolute muscle forces when performing the same relative work (22, 40). These lower absolute forces should require less demand for muscle oxygen and result in less mechanical compression of the active tissue vasculature, thereby allowing for less imbalance between blood supply and demand (26, 44). A recent report by Hunter and Enoka (24) demonstrating a strong relation between absolute force production and muscular endurance time provides indirect evidence for this hypothesis (36). Further support for this muscle mass and strength hypothesis is provided by the finding that the magnitude of gender differences in skeletal muscle fatigability decreases as contraction intensity increases (22, 36). However, the finding that, despite being matched for strength, women still exhibit a fatigue resistance advantage indicates that other mechanisms are involved in mediating the observed gender differences in muscle fatigability (19).

Although differences in neuromuscular activation patterns have not been explored extensively, two studies provide evidence for potential differences with respect to gender and muscle fatigue (21, 45). An intermittent muscle activation pattern, directly associated with an increased endurance time, has been observed in women after immobilization of the elbow flexor muscles (45). Another possible gender difference in neuromuscular activation patterns could be manifested through alterations in synergistic muscle recruitment, although recent evidence suggests that synergistic activation is similar for the elbow flexors between men and women during a fatiguing submaximal contraction (24).

Surface electromyography (EMG) is commonly used to assess muscle fiber action potential activity in skeletal muscle (13). Expression of the EMG signal in the time domain allows for evaluation of neuromuscular activation patterns, inasmuch as a greater amplitude appears to be primarily due to an increase in the number of motor units recruited and an increase in the motor unit discharge rate (2).

The surface EMG signal can also be expressed in the frequency domain by application of the fast Fourier transform (FFT) algorithm to a selected epoch of the interference EMG signal. This application results in creation of a power density spectrum (PDS). During a sustained submaximal contraction, the depolarization and propagation of muscle fiber action potentials are modified. These modifications produce time-dependent changes in the surface EMG signal, which result in a shift of the PDS to the lower frequencies (spectral compression) (20). The distribution of the PDS can be quantified via calculation of its median frequency (MF) (12, 20).

Spectral compression during a fatiguing submaximal contraction has been attributed to a number of underlying physiological factors. One of the most popular hypotheses states that the decrease in muscle fiber conduction velocity seen with fatigue influences the PDS, resulting in spectral compression (11, 30, 31, 39). This is most likely due to an accumulation of metabolites (i.e., H^+ and extracellular K^+) (4, 23, 25, 47), reducing intracellular pH (7) and, thus, decreasing sarcolemma excitability. However, this explanation appears to be incomplete, as a disassociation between MF and conduction velocity is observed during ischemia (52) and different types of muscular contractions (isometric vs. isotonic) (35).

Although the exact mechanisms underlying spectral compression are not fully understood, the resultant shift to lower frequencies during sustained contractions is widely recognized as a noninvasive and localized method of monitoring electrophysiological fatigue processes (20, 27, 29, 32, 34, 48). Because the rate of decline in the MF during a submaximal contraction is approximately linear and highly correlated with endurance time, it has been suggested as a sensitive, objective, and motivation-independent assessment of fatigue-induced changes in an active muscle (20, 32, 38).

The neuromuscular characteristics of the back extensor muscles have been studied extensively (27, 32, 34, 48). When healthy (i.e., free of low back pain) individuals are examined, gender has been shown to be associated with endurance capacity, with women being less fatigable than men (27, 32, 34, 48). Because the lumbar spine is tightly coupled to the gluteus maximus and biceps femoris muscles via the thoracolumbar fascia and ligamentum sacrotuberale, these hip extensor muscles can contribute to the force production (49). Our laboratory has recently demonstrated fatigue-induced alterations in neuromuscular activation patterns of the lumbar and hip extensor muscles (8, 9, 42). Therefore, we wished to examine the endurance capacity and fatigue responses of these muscles during trunk extension exercise, specifically with respect to biological sex.

The purposes of this study were *1*) to evaluate gender differences in the endurance capacity of the back extensors during isometric and isotonic muscular contractions, *2*) to determine the relation between absolute load and endurance time, and *3*) to compare neuromuscular activation and fatigue patterns of the lumbar and hip extensors between men and women during fatiguing moderate-intensity isometric trunk extension exercise.

METHODS

Subjects. Ten female (21.7 ± 3.4 yr old) and 10 male (22.4 ± 2.2 yr old) volunteers were recruited from a university setting to participate in the study. Descriptive statistics are provided in Table 1. Subjects were apparently healthy and recreationally active but were not engaged in a systematic exercise program of the lumbar or hip extensor muscles. The Syracuse University Institutional Review Board approved the experimental protocol, and all subjects provided written informed consent before testing. Potential subjects were excluded if they had a history of chronic low back pain, present back pain, neurological disorder, or any orthopedic or cardiovascular contraindications to exercise.

Experimental design. Subjects visited the laboratory three times. The first visit was a familiarization session, at which time height, body mass, upper body mass (UBM), and torso length (measured in an erect posture from the anterior superior iliac spine to the acromion process) were recorded. During the second visit, lumbar strength was determined, and subjects performed isotonic trunk extension exercise through a 30° range of motion (ROM) at 50% of maximum voluntary contraction (MVC) force (Fig. 1*A*). Subjects were asked to perform as many repetitions as possible, and the test was terminated when the subjects could no longer complete the full ROM or complete the repetitions in the prescribed time (2 s concentric and 2 s eccentric). The final visit was conducted 3–5 days later. During this visit, surface EMG electrodes were placed on the right and left lumbar paraspinal (L_4–L_5), right gluteus maximus, and right biceps femoris muscles. Next, subjects performed an isometric endurance test at 50% MVC that involved holding the upper body in the horizontal plane (Fig. 1*A*). To examine potential differences

Table 1. *Descriptive and performance characteristics of subjects*

Subjects	Age, yr	Body Mass, kg	Height, cm	UBM, kg	Lumbar Strength, kg	Added Load, kg	Isometric Time, s	Isotonic Repetitions
Females	21.7 ± 1.07	67.27 ± 2.08	165.01 ± 1.29	30.60 ± 1.25	43.33 ± 2.13	6.33 ± 1.47	146.02 ± 10.99†	24.30 ± 3.43
Males	22.4 ± 0.69	78.4 ± 3.40*	174.68 ± 1.76*	37.2 ± 1.45*	71.13 ± 3.33*	17.07 ± 1.83*	105.47 ± 7.99	24.00 ± 2.83

Values are means ± SE; *n* = 10. UBM, upper body mass. *Men > women; †women > men ($P < 0.05$).

A

30°

B

Biceps Femoris

Gluteus Maximus

L.L4-L5 Lumbar Extensor

R.L4-L5 Lumbar Extensor

mVolts

0.0   34.7   69.4   104.1
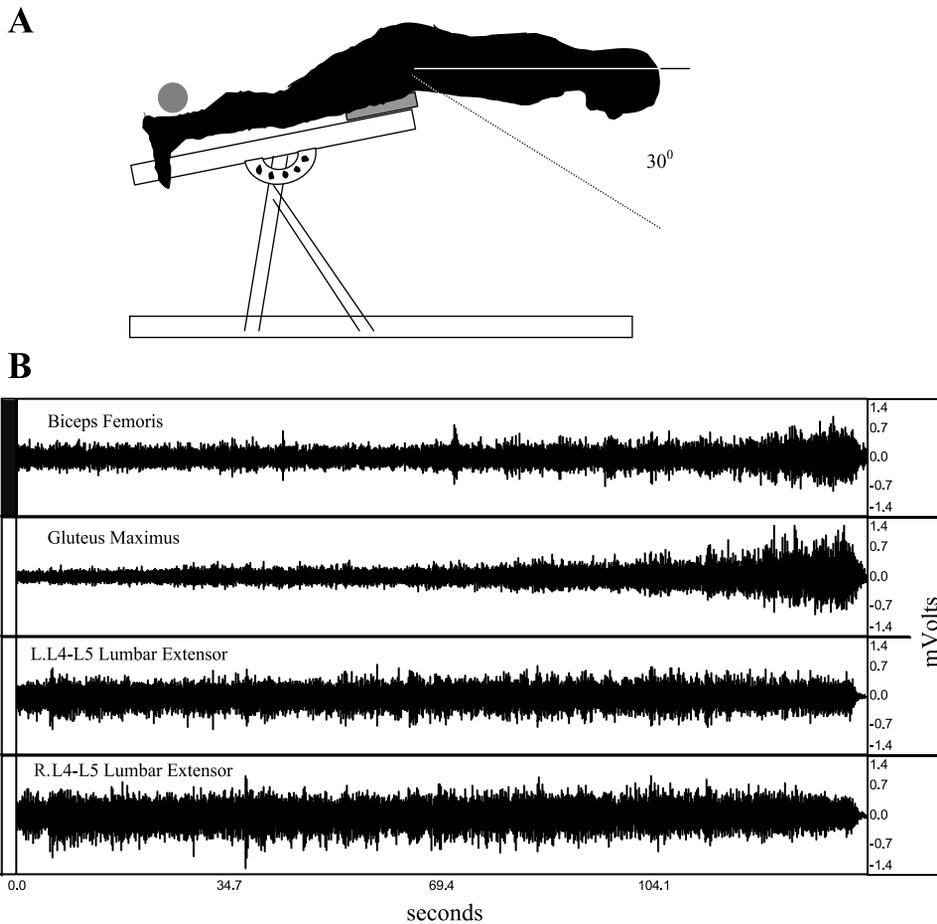
seconds

Fig. 1. *A*: experimental setup. During isotonic exercise, subject performed contractions through a 30° range of motion (2 s concentric, 2 s eccentric). During isometric exercise, subject held her upper body parallel to the ground. An external weight was added to subject's upper body via a weight vest for loading at an intensity of 50% maximal voluntary contraction (MVC). *B*: representative illustration of interference electromyogram (EMG) recorded from biceps femoris, gluteus maximus, and lumbar extensor muscles [left (L.L$_4$–L$_5$) and right (R.L$_4$–L$_5$)] during a fatiguing contraction performed by a female subject.

in neuromuscular activation patterns, we chose to utilize this isometric protocol, because the hip extensor muscles contribute to the force production during trunk extension exercise and are synergistically recruited in association with fatigue (9). Detailed information on all procedures is described below.

Determination of MVC force. To determine lumbar strength, a subject was fitted with a nylon torso harness equipped with a ring at the midsternal region to allow for attachment of a chain. Next, the subject was positioned on a variable-angle Roman chair (Backstrong, Brea, CA) at 15° above the horizontal plane and was attached to a tensiometer (Takei Scientific Instruments, Tokyo, Japan; measurement range 0–300 kg in 1-kg increments) via the harness and chain. The subject crossed his/her arms and placed his/her hands on the opposite shoulders. During the strength assessment, the subject gradually increased force production over the 1st s and then exerted a maximum effort for 2–3 s. Three maximal contractions were performed with a 2- to 3-min rest period between efforts. If the subject continually recorded more force with increasing trials or if the trials were not within 2 kg, additional trials were performed until a plateau was reached. During testing, strong verbal encouragement was provided by the investigators. The lumbar extension strength-testing protocol has been previously described and found to be reliable (intraclass correlation coefficient = 0.97) (8, 9, 37).

During the strength assessment, we considered the MVC force to be a combination of the force exerted on the tensiometer and the UBM (the upper body contributes to force during exercise but does not result in force recorded by the tensiom-

eter). To account for individual differences in UBM, the subject was positioned on the variable-angle Roman chair at 15° relative to horizontal, while the upper body rested on a bedside scale (Acme Medical Scale, San Leandro, CA). When the subject was completely relaxed, UBM was recorded to the nearest 0.01 kg. The same investigator performed the procedure with all subjects to eliminate intertester measurement error. The UBM measurement protocol has been previously described and found to be reliable (intraclass correlation coefficient = 0.99) (8, 9, 37). Next, the subject's MVC force was determined as follows

MVC force = strength (kg)

+ harness and chain weight (0.7 kg) + UBM (kg)

To load the subjects at a relative intensity of 50%, the MVC force was multiplied by 0.50 and UBM was subtracted. The resultant value was then added to the subject's upper body via a weight vest that was adjustable in 1.14-kg increments (WeightVest.com). Strength and loading characteristics are displayed in Table 1.

Isotonic exercise protocol. The subject was positioned on the variable-angle Roman chair and loaded at an intensity of 50% MVC (Fig. 1*A*). The subject then performed isotonic trunk extensions to muscular failure. The subject began with the trunk fully flexed and extended his/her trunk in a smooth, controlled fashion, completing the concentric phase in 2 s. Next, the subject lowered his/her torso during the eccentric phase in 2 s to return to a fully flexed position. A metronome, along with investigator feedback, was utilized to ensure appropriate timing. The exercise was performed

through a 30° ROM, with full extension being parallel to the ground. An electric goniometer located on the right hip provided position output. The test was terminated when the subject could no longer complete the ROM or keep the appropriate timing (2 s concentric, 2 s eccentric). The objective criterion for test termination was two consecutive repetitions with a ≥4° decrement in ROM, despite strong verbal encouragement.

Isometric exercise protocol. On a subsequent day, a subject was positioned on the variable-angle Roman chair and loaded at an intensity of 50% MVC (Fig. 1*A*). The subject was asked to hold his/her unsupported upper body in the horizontal plane for as long as possible (modified Sørenson) (3). During the test, arms were held across the chest. The test was terminated when the subject could no longer maintain the horizontal position (defined as ≥4° reduction in ROM for 2 s, despite strong verbal encouragement).

Electromyography. Before electrode application, the skin was shaved, abraded, and then cleaned with alcohol to minimize skin impedance. EMG signals were recorded with bipolar surface electrodes (Ag-AgCl, 4-cm diameter, 25-mm interelectrode distance) from the left and right L_4–L_5 lumbar paraspinal region, right gluteus maximus, and right biceps femoris muscles. The L_4–L_5 electrodes were placed 1 cm above and below the interspinous space. The gluteus maximus electrodes were placed at the midpoint of a line running from the inferior lateral angle of the sacrum to the greater trochanter. Biceps femoris muscle electrodes were placed in the middle of the leg midway between the gluteal fold and popliteal joint. Reference electrodes were placed with respect to the differential electrodes on bony prominences. Electrode placement was chosen on the basis of the standardized electrode placement atlas of Cram and Kasman (10).

The analog signal was preamplified 100 times (BioAmp 100, Axon Instruments, Foster City, CA) and then amplified 10 times (Cyber Amp 380, Axon Instruments; total gain 1,000). The signal was band-pass filtered between 10 and 600 Hz. The analog signal was digitized at 1,000 Hz with an analog-to-digital board via a data acquisition card (Lab View, National Instruments, Austin, TX). The interference EMG signal was saved for subsequent analysis (Fig. 1*B*).

Treatment of EMG data. Interference EMG data from the fatiguing isometric contraction were arranged in 2,048 sample epochs, windowed (Hamming), and transformed via FFT analysis (Lab View). The resulting power spectrum was quantified by calculating the MF with the following equation (Fig. 2*A*)

$$\int_0^{MF} Sm(f)\, df = \int_{MF}^{\infty} Sm(f)\, df$$

where $Sm(f)$ is the power density spectrum of the EMG signal (2). To account for gender differences in adipose tissue, inasmuch as it has been demonstrated to act as a low-pass filter (5), MF was normalized to the initial MF from the first 2,048-sample epoch. The normalized MF was then plotted against time, and the resulting slope was calculated (MF_{slope}; Fig. 2*B*).

Additionally, root-mean-square (RMS) EMG was calculated in 2,048 sample epochs. Next, a mean RMS EMG value was determined for each 10th percentile of endurance time. To assess muscle activation pattern differences with fatigue, the EMG values were normalized to the first 10th percentile of endurance time and expressed as a percent change.

Statistical analysis. A one-way analysis of variance (ANOVA) was performed to assess potential differences in endurance time between men and women. Subsequently, an
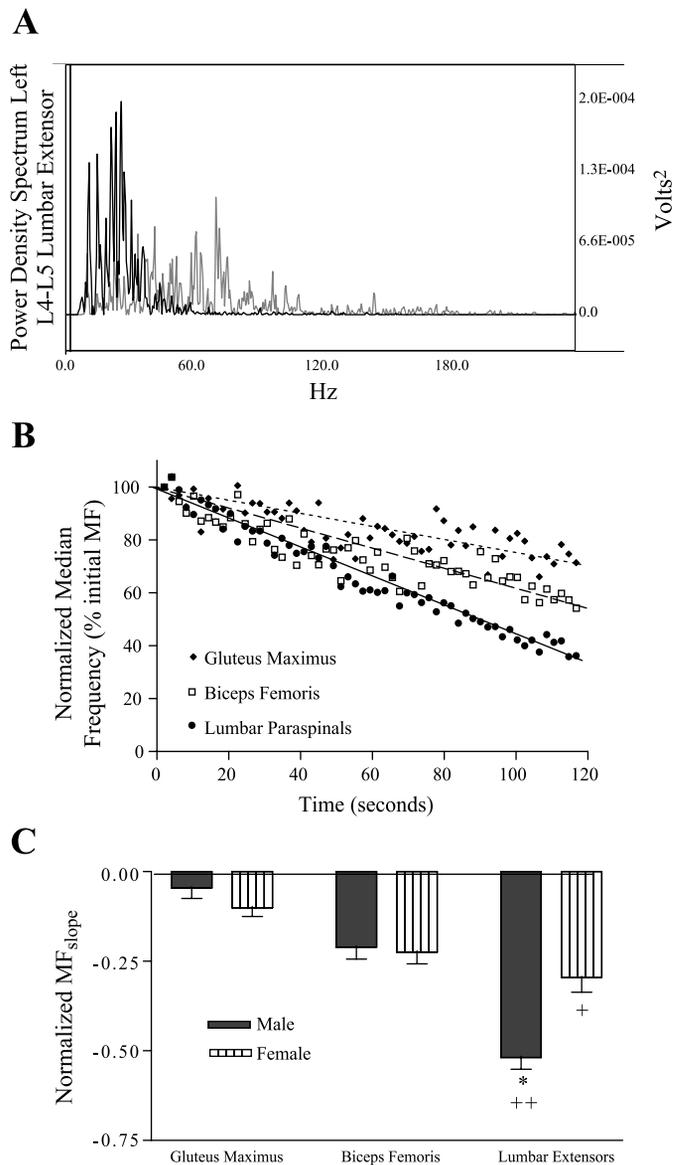

Fig. 2. *A*: representative sample of a power density spectrum from a 2,048-sample epoch of left lumbar extensor interference EMG signal from 1 male subject at start of contraction [gray trace; median frequency (MF) = 88 Hz] and end of contraction (black trace; MF = 38 Hz). *B*: normalized MF of lumbar extensor, gluteus maximus, and biceps femoris muscles plotted as a function of endurance time for 1 male subject. Resultant linear regression slopes were calculated for each subject. *C*: relative fatigability (MF_{slope}) of lumbar and hip extensor muscles for men and women during isometric back extensor endurance task. *Men > women; +lumbar extensors > gluteus maximus; ++lumbar extensors > biceps femoris > gluteus maximus ($P < 0.05$).

analysis of covariance was performed with endurance time covaried for absolute load. The relation between absolute load and endurance time was evaluated with three different polynomial regression models. The first model assessed the relation between absolute load and endurance time in the pooled sample; the second and third models evaluated this relation separately within each gender.

No differences were observed in any of the EMG responses between the right and left lumbar paraspinal muscles; thus data from the right and left sides were pooled for further analyses. For the MF_{slope} data, a two-way repeated-measures

ANOVA was performed (between-subjects main effect: gender; within-subject main effect: muscle group). Additionally, multiple regression was used to evaluate the contribution of different muscles to isometric trunk extension endurance time. Individual regression analyses were performed with endurance time entered as the dependent variable, whereas normalized MF values for the lumbar paraspinal, gluteus maximus, and biceps femoris muscles were entered as the independent variables. For each subject, the R^2 and semipartial r^2 values were determined. From these data, mean R^2 and mean semipartial r^2 values were determined for each gender. Shared variances [full model $R^2 -$ (lumbar extensors semipartial r^2 + gluteus maximus semipartial r^2 + biceps femoris semipartial r^2)] and unexplained variances were calculated. The semipartial r^2 value is interpreted as the percentage of variance in endurance time (the dependent variable) uniquely attributable to the given independent variable. Independent t-tests were used to compare percentage of explained variances between men and women.

For the normalized RMS EMG data, a three-way repeated-measures ANOVA was performed (between-subjects main effects: gender and muscle; within-subject main effect: percentile of endurance time). Scheffé's post hoc analysis was used to test significant main effects and/or interactions. For all statistical analysis, an α-level of $P \leq 0.05$ was considered significant. P values, effect sizes (η^2), and power are reported where appropriate. Values are means ± SE. The SPSS (version 10.0, Chicago, IL) and STATA (version 7.0, College Station, TX) statistical packages were used for data analysis.

RESULTS

Isometric and isotonic contractions. Women exhibited significantly greater endurance on the isometric test than men (146.0 ± 10.9 vs. 105.4 ± 7.9 s, $P =$ 0.008, $\eta^2 = 0.33$, power = 0.81; Table 1). However, there was no gender difference in the number of isotonic repetitions performed (24.3 ± 3.4 and 24.0 ± 2.8 repetitions for women and men, respectively, $P =$ 0.623, $\eta^2 = 0.01$). The gender difference observed during the isometric contraction was not influenced by torso length, as there were no significant differences between men and women (68.84 ± 0.94 vs. 66.76 ± 0.71 cm, $P = 0.098$, $\eta^2 = 0.15$), nor was there a relation between torso length and endurance time ($R^2 = 0.16$, $P = 0.079$).

Spectral compression of the interference EMG. A significant gender × muscle interaction was observed in MF_{slope} ($P < 0.001$, $\eta^2 = 0.29$, power = 0.99). Women demonstrated a similar MF_{slope} in the biceps femoris and lumbar extensors, whereas the lumbar musculature fatigued more (a greater MF_{slope} decrease) than the biceps femoris in men (Fig. 2C). Additionally, men demonstrated a more pronounced lumbar paraspinal MF_{slope} than women (−0.5186 ± 0.03 vs. −0.2962 ± 0.08, $P < 0.000$; Fig. 2C). For men and women, the MF_{slope} of the lumbar paraspinal muscles was greater than the MF_{slope} of the gluteus maximus muscles [−0.5186 ± 0.03 vs. −0.0452 ± 0.03 ($P < 0.001$) for men and −0.2962 ± 0.04 vs. −0.1007 ± 0.02 ($P = 0.001$) for women; Fig. 2C]. Conversely, the MF_{slope} of the lumbar paraspinals was greater than the MF_{slope} of the biceps femoris among men (−0.5186 ± 0.03 vs. −0.2112 ± 0.03, $P < 0.001$) but not among women (−0.2962 ± 0.08 vs. −0.2249 ± 0.03, $P = 0.32$; Fig. 2C). No significant gender differences in MF_{slope} were observed for the biceps femoris or gluteus maximus muscles ($P = 0.767$ and 0.169 for women and men, respectively).

The three-variable multiple regression model (normalized MF of the lumbar extensor, gluteus maximus, and biceps femoris muscles) explained 95.8 and 93.7% of the variability in endurance time for men and women, respectively (Fig. 3). MF shifts of the lumbar extensors throughout the fatiguing contraction influenced endurance time more in men than in women (44.9 vs. 19.1%, $P = 0.021$, $\eta^2 = 0.28$, power = 0.67; Fig. 3).

Muscle activation patterns. A significant muscle × percentage of endurance time interaction was observed for the normalized RMS EMG ($P = 0.001$, $\eta^2 = 0.27$, power = 1.0). Further analysis revealed more recruitment of the gluteus maximus than the lumbar extensor and biceps femoris muscles as subjects became fatigued (Fig. 4). The synergistic muscle activation patterns between men and women were strikingly similar, and no main effect or interaction for gender was observed (Fig. 4; $P = 0.973$, $\eta^2 = 0.00$).

Endurance time and absolute load. When absolute load was regressed on endurance time (with all subjects entered into the model), a significant quadratic relation was observed, with 34.1% of the variance in endurance time being explained by absolute load ($R^2 = 0.341$, $P = 0.037$; Fig. 5). However, this relation did not
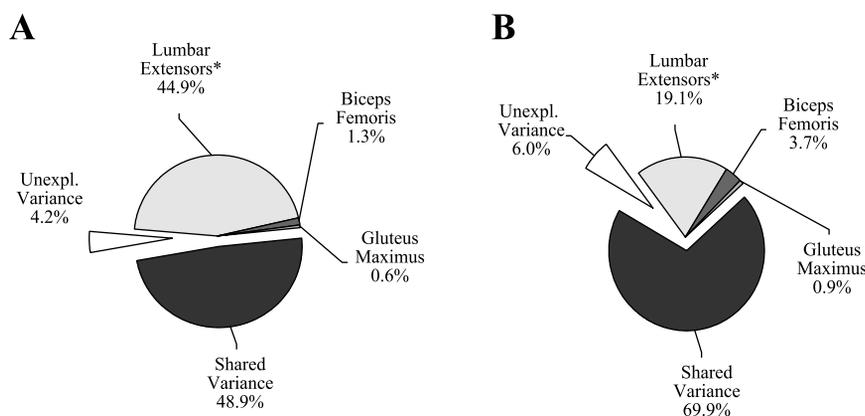
A

B

Fig. 3. Percentage of explained variance in endurance time by muscle fatigue (median frequency) in lumbar extensor, biceps femoris, and gluteus maximus muscles in men (A) and women (B). Explained variances were determined by calculating mean semipartial r^2 for muscles on each subject individually, whereas shared variance was determined by subtracting summed semipartial r^2 values for each muscle from R^2 for full models. Unexpl Variance, unexplained variance. *Male lumbar extensors semipartial r^2 > female lumbar extensors semipartial r^2 ($P \geq 0.05$).
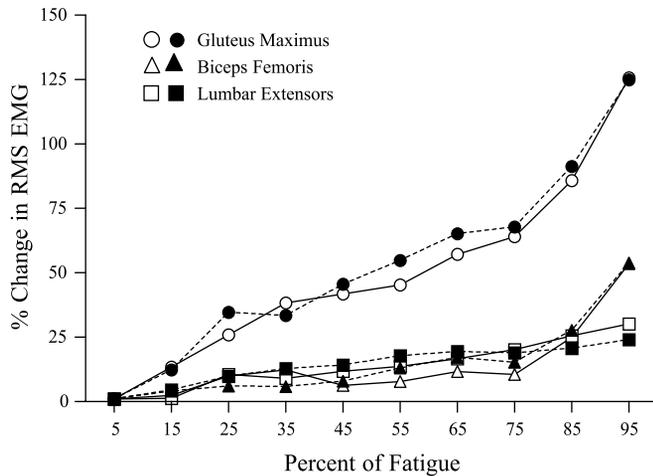
Fig. 4. Synergistic muscle activation patterns during an isometric back extension endurance task in men (filled symbols) and women (open symbols). Values are expressed relative to mean root-mean-square (RMS) EMG at start of exercise (1st–10th percentile of fatigue). SE bars have been omitted for the sake of clarity. EMG for lumbar extensors represents pooled EMG for left and right L_4–L_5 extensor musculature. A significant muscle $\times$ percentage of fatigue interaction was observed, indicating that gluteus maximus was recruited to a greater extent than lumbar extensor and biceps femoris muscles as subjects became fatigued. No main effect or interaction for gender was observed.

hold true when men and women were evaluated separately ($R^2 = 0.054$ and 0.040 for men and women, respectively, $P = 0.442$ and 0.517, respectively; Fig. 5). Similarly, when endurance time during the isometric test was statistically covaried for absolute load (UBM + added load), the previously observed gender differences disappeared (estimated marginal means with the covariate load equal to 44.95 kg: 136.34 ± 15.4 and 114.26 ± 15.4 s for women and men, respectively, $P = 0.43$, $\eta^2 = 0.07$).

DISCUSSION

The major finding of this study is that men and women differ in their patterns of fatigue (as interpreted through the spectral compression findings). It appears that women fatigue similarly in the biceps femoris and lumbar extensors, whereas men fatigue to a greater extent in the lumbar extensors than in the biceps femoris. Additionally, it appears that the fatigue-induced changes in the lumbar extensor muscles influence endurance time more in men than in women and that these differential gender responses are not related to differences in the neuromuscular activation strategy utilized. Another interesting finding is that women demonstrated better muscular endurance than men only during isometric contractions, and when endurance time was adjusted for absolute load, no differences were observed.

Interpretation of gender differences in spectral compression patterns. We did observe gender differences in the frequency shifts of the EMG power spectrum with fatigue during the isometric contraction (Figs. 2C and 3). Women demonstrated a similar fatigability in the

biceps femoris and lumbar extensors, whereas men demonstrated greater fatigability in the lumbar musculature than in the biceps femoris (Fig. 2C). The finding of a more pronounced fatigability of the lumbar extensors in men than in women is in agreement with previous reports (27, 32, 48). However, because previous reports have not loaded subjects at the same relative intensity, inferring from the results of these studies has been difficult. Our findings of differences in lumbar muscle fatigability when subjects are loaded at the same relative load provide evidence of gender differences in the endurance capacity of the paraspinal musculature. Additionally, fatigability of the lumbar musculature influenced endurance time more in men than in women, suggesting gender differences in fatigue patterns. Specifically, lumbar muscle fatigue accounted for 45% of the variance in performance time for men, whereas in women it exerted considerably less influence on performance time (19%).

Evaluation of the frequency distribution change of the interference EMG signal during a sustained submaximal isometric contraction has been widely promoted as a valuable technique for evaluating the fatigability of the back extensor muscles (32, 48). In general, spectral analysis is considered to be a sensitive method to assess fatigue-induced changes within a muscle, because it displays a high correlation with endurance time over a wide variety of contraction intensities (20, 32, 38). Therefore, these data provide evidence that gender differences in muscular endurance capacity are related to physiological issues and are not an artifact of subject motivation. Thus it appears that the lumbar musculature is more fatigue resistant in women than in men. Findings from the present study also help describe the influence of localized muscle fatigue on endurance test performance. Our finding that frequency shifts in the lumbar mus-
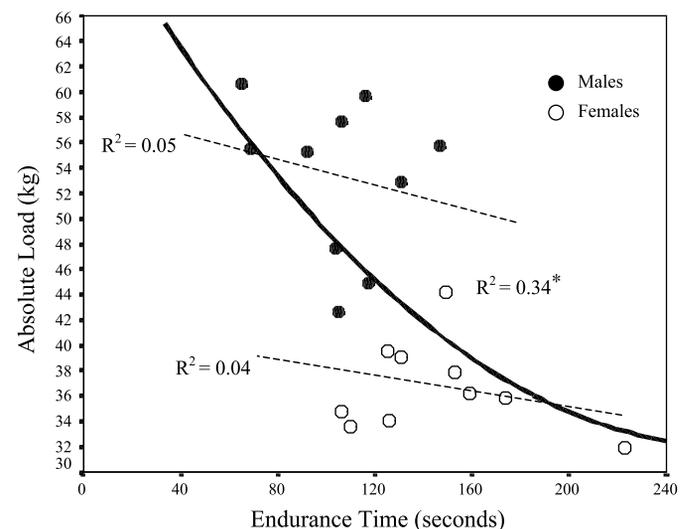

Fig. 5. Relation between absolute load and endurance time. When men and women are entered into the same regression model, absolute load explains 34.1% of variance in endurance time. However, when evaluated by gender, there is no relation between absolute load and endurance time. *$P \le 0.05$.

culature are related more to endurance time in men than in women indicates that synergistic muscles do not fatigue in a similar manner. Understanding why fatigability patterns differed between the genders is difficult. Intuitively, one would hypothesize that this fatigue pattern difference may be the result of activation patterns, with the men failing to recruit the synergistic hip extensors. However, because we found this not to be the case, the reason for the apparent gender differences remains unclear. It is plausible that this finding is related to anatomic structure, inasmuch as women have a wider pelvis and more pronounced lordosis of the spine (16). Further research is needed to determine whether this observation can be verified for other muscle groups.

A more complete understanding of our findings depends on the interpretation of spectral compression during a sustained submaximal contraction. There is strong evidence that spectral compression of the interference EMG signal during a sustained submaximal contraction is due to a slowing of conduction velocity caused by metabolic shifts (decreased muscle pH) in the active skeletal muscle (4, 7, 11, 23, 25, 30, 31, 39, 47). Following this interpretation, it appears that during the isometric contraction the lumbar musculature undergoes this metabolic shift faster in men than in women and that this altered intracellular state of the muscle directly influences endurance time to a greater extent in men than in women. This finding is in agreement with a recent study from Kent-Braun and colleagues (28), who reported a greater reliance on glycolytic metabolism during intermittent isometric contractions in men than in women, as assessed by increased intracellular P_i and $H_2PO_4^-$ concentrations and decreased pH. On the basis of the idea of gender differences in muscle metabolism, one could postulate that the underlying cause of gender differences in spectral compression patterns may be related to muscle morphology. Gender differences in muscle fiber types have been reported, with men having a greater fiber size ratio of type II to type I muscle fibers (1, 33, 34, 43, 46). However, because we did not find a female advantage in fatigue resistance during the isotonic task, this explanation seems unlikely. It has been suggested that spectral compression of the EMG signal is due to impaired circulation (20, 35). Merletti and colleagues (39) demonstrated that MF decreases with applied ischemia, despite the absence of muscle fatigue. Therefore, our spectral analysis findings could provide evidence of gender differences in perfusion, although at this time this is speculative.

We must use caution in the interpretation of our spectral analysis findings on the basis of the limited understanding of the MF shifts with fatigue. There are many factors possibly affecting the spectral compression of the EMG signal. For example, computer simulation studies indicate that increased motor unit synchronization may result in shifts of the PDS to the lower frequencies (15, 51). However, because this synchronization also causes an increase in the amplitude of the EMG signal (51) and because we found no gender differences in this parameter, the explanation of an increased motor unit synchronization in men (vs. women) seems unlikely. Other influential variables affecting the PDS are EMG bursting and muscle temperature. With respect to EMG bursting, we did qualitatively observe periodic bursting; however, this bursting activity appeared to be present in both genders. It is known that muscle temperature is highly correlated to MF (39), and because women have greater amounts of subcutaneous adipose tissue, it is possible that this resulted in an increased muscle temperature compared with men, thus affecting our MF findings; yet core temperature is not generally thought to vary with gender.

Muscle activation patterns. We did not observe any gender differences in neuromuscular activation patterns, and the synergistic muscle activation strategies utilized by men and women appear to be almost identical (Fig. 1). This finding is in agreement with a recent report from Hunter and Enoka (24) and in disagreement with a report from Semmler et al. (45). However, in the latter study, gender differences were observed after limb immobilization; therefore, it is possible that a greater perturbation to the neuromuscular system is required for gender differences in activation patterns to be evident. The finding of the hip extensor muscles being synergistically recruited with fatigue to allow for continuation of isometric trunk extension exercise is similar to previous findings from our laboratory evaluating isotonic muscle activation patterns (8, 9, 42).

Is muscular endurance dependent on absolute load, contraction type, and muscle blood flow? Some observations from this study suggest that endurance is at least somewhat explained by the absolute load encountered by a participant during an isometric endurance task. Two findings (when considered collectively) seem to indicate that absolute load influences endurance time: *1*) gender differences in endurance time are insignificant when covaried for absolute load, and *2*) absolute load explains 34% of the variance in endurance time. Our findings are in agreement with those recently reported by Hunter and Enoka (24) and Kent-Braun et al. (28). In the former study, women exhibited endurance times 118% longer than men during a low-intensity contraction (20% MVC) of the elbow flexor muscles. However, when these values were covaried for target force, no gender difference was found. Our finding that 34% of the variance in fatigability is explained by absolute load is slightly higher than the 24% reported by Kent Braun et al. and lower than the 64% reported by Hunter and Enoka. Additionally, our finding of no relation between absolute load and endurance time when men and women are analyzed separately is in agreement with Maughan et al. (36). Our observations seem to indicate that the relation of absolute load to endurance time exists only when men and women are analyzed collectively (Fig. 5). Therefore, this finding raises questions as to the true effect of absolute load on endurance time, as one would expect this relation to hold true within genders if this relation was physiologically meaningful. Further study is needed to

clarify the nature of this relation, as it is possible that our small range of values for absolute load was problematic in this regard. As our findings presently stand, it is not possible to speculate on whether the relation between absolute load and endurance time would increase or decrease in magnitude with the addition of more data points. To the authors' knowledge, this is the first report on the absolute force-fatigability relation for the back extensor muscles.

The importance in understanding the role of absolute load on endurance capacity relates to issues surrounding muscle perfusion during exercise. If, indeed, the gender differences in muscular endurance are mediated from differences in intramuscular blood flow, then one would expect a strong relation between absolute load and endurance time, because intramuscular fluid pressure has been found to be linearly related to muscle force (44). Although the data from this study (evaluating the impact of absolute load on endurance time) are somewhat contradictory and difficult to interpret, this study does provide indirect evidence in support of the intramuscular blood flow hypothesis. Although we did not directly assess muscle blood flow, our findings of no gender differences during isotonic contractions, but differences during isometric contractions, suggest that contraction type plays a role in these differences in muscle fatigability. Although there are several differences between isometric and isotonic contractions, the difference that is most relevant to this study involves differences in muscle perfusion. It has long been known that rhythmic muscle contractions allow for a greater degree of muscle perfusion due to enhanced flow from the muscle pump and less intramuscular pressure compared with isometric contractions (6, 17). Therefore, the finding that women demonstrate a greater fatigue resistance during the isometric, but not isotonic, contractions provides evidence in support of muscle perfusion differences between the genders. This is a contrary finding with respect to those reported by Fulco and colleagues (19). In their study, men and women were matched for strength of the adductor pollicis, and gender differences in muscle fatigue and endurance capacity were still observed during an isometric contraction of 50% MVC. Because their findings suggest that gender differences are not related to the muscle mass and strength hypothesis, future research is needed to fully elucidate this relation. The discrepant findings could be related to differences in the muscle group tested, as it is well known that the recruitment range of motor units varies with the respective muscles tested. For example, in some muscles (i.e., first dorsal interosseus and adductor pollicis), all the motor units are recruited when force reaches 50% MVC, whereas in other muscles (i.e., biceps brachii and tibialis anterior), motor units are continually recruited up to ~85% MVC (12). Thus it is possible that the respective muscle groups tested between the studies are distinctly different. Unfortunately, to our knowledge, the motor unit recruitment range of the lumbar or hip extensor muscles is unknown.

Few studies have evaluated gender differences in muscular endurance using an isometric and isotonic model (36). Our findings of gender differences only during isometric contractions are in disagreement with the findings of Maughan et al. (36). In their study, one group of subjects performed isometric contractions using the knee extensors, whereas a different group performed isotonic contractions with the elbow flexors. At a load of 50% maximal strength, women had greater muscular endurance capacity during the isotonic, but not isometric, contractions. A possible explanation for the contrasting findings between our study and that of Maughan et al. could be differences in muscle groups evaluated. However, a more probable explanation is that because their study was not a within-subject design, between-group differences in muscular endurance capacities may have influenced their findings with respect to contraction type.

The contraction intensity utilized in the study of muscle fatigability has direct impact on the findings, as the magnitude of gender differences typically decreases as contraction intensity increases (22, 36). In a recent review article by Hicks et al. (22), the relation between contraction intensity and the magnitude of the female advantage in fatigue resistance was estimated on the basis of nine studies (the majority of which used an isometric contraction protocol). Our finding of a 33% difference in muscular endurance capacity between women and men is similar to their estimate. This relation of gender differences in muscle fatigability and contraction intensity may explain some of the discrepant findings presented in this study. For example, our finding of the relation between absolute load and endurance time being less than that previously reported by Hunter and Enoka (24) is probably related to the different contraction intensities used, as they employed an intensity of 20% MVC compared with the intensity of 50% MVC used in the present study. Because the force-fatigability curve typically reveals a hyperbolic relation (14), it seems plausible that a lesser relation would be present at higher contraction forces.

In conclusion, during isometric trunk extension exercise, gender differences in spectral compression of the individual muscle groups occurred differentially between men and women, indicating an altered pattern of muscle fatigability, with fatigue of the lumbar musculature influencing endurance time more in men than in women. These findings were not explained by gender differences in synergistic muscle activation patterns. Additionally, we observed gender differences in the muscular endurance capacity of the back extensor muscles during isometric trunk extension but not during isotonic exercise. This finding, along with absolute load being in part responsible for isometric muscular endurance performance, provides evidence that gender differences in fatigability are mediated through the muscle mass and strength hypothesis. These findings could have implications for exercise training and prescription, as well as clinical practice and testing of the trunk extensor musculature.

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