Fatigability of the elbow flexor muscles for a sustained submaximal contraction is similar in men and women matched for strength

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Hunter, Sandra K., Ashley Critchlow, In-Sik Shin, and Roger M. Enoka. Fatigability of the elbow flexor muscles for a sustained submaximal contraction sustained in men and women matched for strength. J Appl Physiol 96: 195–202, 2004. —The purpose of this study was to compare the time to task failure for a submaximal fatiguing contraction sustained with the elbow flexor muscles by men and women who were matched for strength (n = 20, 18–35 yr). The maximal torque exerted at the wrist was similar for the men and women (64.5 ± 8.7 (SD) vs. 64.5 ± 8.3 N·m; P > 0.05), which meant that the average torque exerted during the fatiguing contraction [20% of maximum voluntary contraction (MVC)] was similar for the two sexes. The time to task failure was similar for these strength-matched men and women (819 ± 306 vs. 864 ± 391 s; P > 0.05). The mean arterial pressure was similar at the beginning of the contraction for men (97 ± 12 mmHg) and women (96 ± 15 mmHg; P > 0.05) and at task failure (134 ± 18 vs. 126 ± 26 mmHg; P > 0.05, respectively). Furthermore, the increases in heart rate, torque fluctuations, and rating of perceived exertion during the fatiguing contraction were similar for the two sexes. However, the electromyogram (EMG) activity differed for the men and women: the rate of increase in the average of the rectified EMG (% peak MVC) for all the elbow flexor muscles was less for the women compared with the men (P < 0.05). Furthermore, the bursts of EMG activity for the elbow flexor muscles increased toward exhaustion for all subjects but at a greater rate for the women compared with the men (P < 0.05). The results indicate that strength-matched men and women experienced similar levels of muscle fatigue and cardiovascular adjustments during a sustained low-intensity isometric contraction, despite differences in the EMG activity for the two groups of subjects.

The time to task failure for an isometric contraction sustained at a submaximal intensity is greater for women compared with men (4, 12, 14, 17, 35). One possible explanation for this sex difference is that men, who are usually stronger than women, sustain greater absolute forces when the target force is based on an individual’s strength. For example, the time to task failure for fatiguing contractions performed at 15 and 20% of maximal voluntary contraction (MVC) force with the elbow flexor muscles was greater for women compared with men but not when the times were covaried with the target force (14, 17). In these studies, stronger individuals exerted greater absolute forces, had briefer times to task failure, and generated a greater pressor response; the pressor response is a reflex-mediated increase in mean arterial pressure due to metabolite accumulation that attempts to rectify the mismatch between perfusion and metabolism during an isometric contraction (24, 28). These results suggest that men experienced greater intramuscular pressures and therefore greater mechanical compression of the feed arteries perfusing the active muscle (1), which enhanced the accumulation of metabolites and heightened the pressor response. Consistent with this rationale, Russ and Kent-Braun (29) found that women experienced less muscle fatigue when performing intermittent maximal contractions with the tibialis anterior muscle but that fatigue was similar for men and women when blood flow to the muscle was occluded.

When fatiguing contractions are performed with a hand muscle, stronger individuals also show briefer times to task failure for a sustained submaximal contraction (14). This association, however, has not been observed for all muscles and tasks. For example, the time to task failure was not related to the initial strength of the individual for the handgrip and knee extensor muscles, even though women sustained the low-intensity contractions for a longer duration than the men (22, 35). Furthermore, the time to task failure for a series of intermittent submaximal contractions with a hand muscle, which permits muscle perfusion between contractions, was longer for strength-matched men and women (7). Nonetheless, no study has directly assessed the contribution of absolute strength and the associated pressor response to the sex difference in time to task failure for a sustained contraction of a large muscle group in which the intramuscular pressures are likely to be large.

The purpose of this study was to compare the time to task failure for a submaximal fatiguing contraction sustained with the elbow flexor muscles by men and women who were matched for strength. The strategies used by the subjects to perform the task were characterized by measurement of the pressor response [mean arterial pressure (MAP) and heart rate] and the EMG activity of multiple muscles. The pressor response indicated the cardiovascular adjustments during the task. The EMG activity [average rectified EMG (AEMG) and bursting activity] was measured for comparison with previously observed sex differences between men who were stronger than women (15–17, 33). Despite differences in the rate of increase in the average EMG and the bursts of EMG activity for the two groups of subjects, the time to task failure and the pressor response were similar for the strength-matched men and women. Preliminary accounts of these results have been presented in abstract form (13).
METHODS

From the 67 healthy young adults (18–34 yr) who volunteered to participate in the study, 15 men and 16 women (22 ± 4 SD yr) were selected to complete the experimental protocol. None of the subjects had any known neurological disorder or cardiovascular disease, and all were naive to the experimental protocol and procedures. Before participation in the study, all subjects gave informed consent, and the Human Subjects Committee at the University of Colorado approved the protocol.

From the sample of 15 men and 16 women who completed the experimental protocol, 10 men and 10 women (22 ± 4 yr) were matched for strength on the basis of the torque exerted at the wrist. Each pair of subjects was matched within 5% of the maximal torque exerted by the elbow flexor muscles. The physical activity level for each subject was assessed by estimating the relative amount of kilocalorie expenditure per week by using a physical activity questionnaire (21). The physical activity levels are reported as metabolic equivalents (MET)-h/wk. Arm dominance during the task was determined using the Edinburgh Handedness Inventory (26); all subjects were right-handed. The day of the menstrual cycle on which the experimental protocol was performed was recorded for each female participant. The first day of menstruation was considered as day 1 of the cycle.

Mechanical Recording

Subjects were seated upright in an adjustable chair with the non-dominant arm abducted slightly and the elbow resting on a padded support. The elbow joint was flexed to 1.57 rad so that the forearm was horizontal to the ground and the force at the wrist was directed upward when the elbow flexor muscles were activated voluntarily. Two nylon straps were placed vertically over each shoulder to restrain the subject and minimize shoulder movement. The hand and forearm were placed in a modified wrist-hand-thumb orthosis (Orthomerica, Newport Beach, CA), and the forearm was placed midway between pronation and supination. The forces exerted by the wrist in the vertical and horizontal (side-to-side) directions were measured with a force transducer (Force-Moment Sensor, JR-3, Woodland, CA) that was mounted on a custom-designed, adjustable support. The orthosis was rigidly attached to the force transducer. The forces detected by the transducer were recorded online by using a Power 1401 A-D converter and Spike2 software [Cambridge Electronics Design (CED), Cambridge, UK]. The force exerted in the vertical direction was displayed on a 17-in. monitor located 1.5 m in front of the subject. The force signal was digitized at 500 samples/s.

Electrical Recordings

EMG signals were recorded with bipolar surface electrodes (Ag-AgCl, 8-mm diameter; 16 mm between electrodes) that were placed over the long head of biceps brachii, the short head of biceps brachii, brachioradialis, and triceps brachii muscles. Reference electrodes were placed on a bony prominence at the elbow or shoulder. The EMG of the brachialis muscle was measured with an intramuscular bipolar electrode consisting of two stainless steel wires (100-μm diameter) that were insulated with Formvar (California Fine Wire, Grover Beach, CA). One wire in each pair had the insulation removed for ~2 mm to increase the recording volume of the electrode. The electrode was inserted into the muscle 4–5 cm proximal to the antecubital fold with a hypodermic needle that was removed immediately after insertion. A surface electrode (8-mm diameter) placed on a bony prominence served as the reference electrode. The EMG signal was amplified (500–2,000×) and band-pass filtered (13–1,000 Hz for the surface and intramuscular EMG) with Coulbourn modules (Coulbourn Instruments, Allentown, PA) before being recorded directly to computer using the Power 1401 A-D converter (CED) and displayed on an oscilloscope. The EMG signals were digitized at 2,000 samples/s.

Cardiovascular Measurements

Heart rate and blood pressure were monitored throughout the fatiguing contraction with an automated beat-by-beat, blood pressure monitor (Finapres 2300, Ohmeda, Madison, WI). The blood pressure cuff was placed around the middle finger of the relaxed, dominant hand with the arm placed on a table adjacent to the subject at heart level. The blood pressure signal was recorded online to a computer at 500 samples/s.

Experimental Protocol

Before the experimental session, each subject visited the laboratory for an introductory session to become familiar with the equipment and procedures by performing several trials of the MVC task and practicing contractions to the 20% MVC target force. All subjects were naive to the experimental protocol and procedures before the familiarization session. The protocol comprised an assessment of the MVC force for the elbow flexor and elbow extensor muscles, determination of the EMG-force relations for the elbow flexor muscles, and performance of a fatiguing contraction. Within 10 s of completion of the fatiguing contraction, an MVC was performed with the elbow flexor muscles.

MVC torque. Each subject performed three MVC trials with the elbow flexor muscles, followed by three trials with the elbow extensor muscles. The MVC task consisted of a gradual increase in force from zero to maximum over 3 s, with the maximal force held for 2–3 s. The force exerted by the wrist was displayed on a 17-in. monitor, and each subject was verbally encouraged to achieve maximal force. There was a 60-s rest between trials, and the visual gain was varied between trials (9). If the peak forces from two of the three trials were not within 5% of each other, additional trials were performed until this was accomplished. The greatest force achieved by the subject was taken as the MVC force and used as the reference to calculate the 20% target level for the fatiguing contraction. The MVC torque was calculated as the product of MVC force and the distance between the elbow joint and the point at which the wrist was connected to the force transducer. The calculated torque was used to match the men and women for strength and to determine the target values for the submaximal contractions.

EMG activity. The EMG activity of the involved muscles was recorded in standardized tasks so that the EMG-torque relation could be compared between men and women in the nonfatigued state. The subject performed a sustained constant-force contraction with the elbow flexor muscles for 6 s at target values of 20, 40, and 60% MVC torque. The subject was given a 30-s rest between each contraction. The similarity of these relations for the two groups of subjects ensured that changes in EMG during the fatiguing contraction represented physiological adjustments and were not due to differences in recording conditions.

Fatiguing contraction. The fatiguing contraction of the elbow flexor muscles was performed at a target value of 20% MVC torque. The subject was required to match the vertical target torque as displayed on the monitor and was verbally encouraged to sustain the torque for as long as possible. The fatiguing contraction was terminated when the torque declined by 10% of the target value for greater than ~5 s or when the subject lifted the elbow off the support for greater than ~5 s, despite strong verbal encouragement to maintain the task. Neither the subject nor the investigator who terminated the task knew the time during the task.

An index of perceived effort, the rating of perceived exertion (RPE), was assessed with the modified Borg 10-point scale (2). The subjects were instructed to focus the assessment of effort on the arm muscles performing the task. The scale was anchored so that 0 represented the resting state and 10 corresponded to the strongest contraction that the arm muscles could perform. The RPE was measured at 30-s intervals during the fatiguing contraction.
Data Analysis

All data collected during the experiments were recorded on line using a Power 1401 analog-to-digital converter (CED) and analyzed offline by using the Spike2 data-analysis system (CED).

The MVC torque was quantified as the peak value achieved during the MVC. Similarly, the maximal EMG for each muscle was determined as the average value over a 0.5-s interval that was centered about the peak rectified EMG. The rectified EMG of the constant-torque contractions for the elbow flexor muscles performed at 20, 40, and 60% of MVC torque was averaged over the middle 4 s of the 6-s contraction.

The fluctuations in torque during the fatiguing contraction were quantified in the vertical and horizontal (side-to-side) directions as the SD of torque for the first 30 s; 15 s on both sides of 25, 50, and 75% of time to task failure; and the last 30 s of the time to task failure.

The EMG activity of the elbow flexor muscles and elbow extensor muscles during the fatiguing contraction was quantified in two ways: 1) for statistical purposes, as averages of the rectified EMG (AEMG) over the first 30 s; 15 s on both sides of 25, 50, and 75% of time to task failure; and the last 30 s of the time to task failure for the fatiguing contraction; and 2) for graphic presentation, as the AEMG for every 1% of the time to task failure. The EMG was normalized to the peak EMG obtained during the MVC.

Low-intensity contractions of long duration are characterized by bursts of EMG activity, which were quantified by the process described previously (15–17) and shown in Fig. 1. The rectified EMG signal was 1) smoothed with a low-pass filter at 2 Hz for surface EMG signals and at 3.8 Hz for the intramuscular EMG (brachialis); 2) differentiated over five-point averages; and 3) divided by the AEMG so that muscles with different EMG amplitudes could be compared. The differentiated signal represents the rate of change for the low-pass filtered EMG signal and was used to identify rapid changes in the EMG signal. A burst was identified when the smoothed, differentiated EMG signal increased by >0.20 s⁻¹ for the surface EMG and 0.23 s⁻¹ for the intramuscular EMG. These values represented 3 standard deviations above the mean of the smoothed, differentiated EMG signal. The 3-SD criteria was based on EMG records from fatigue contractions of the present data set when the EMG signal displayed minimal bursting during the contraction. The end of a burst was identified as the time when the smoothed EMG signal decreased to the same amplitude as at the start of the burst. When the EMG signal did not decline to the same EMG amplitude at the start of the burst, however, the end of the burst was then identified as the time that the differentiated EMG signal became most negative before the start of the next burst. This criterion represented the time at which the signal decreased most rapidly before the beginning of the next burst. The start of two bursts was constrained to be >2 s apart and the minimum burst duration was 0.5 s.

Heart rate and MAP recorded during the fatiguing contraction were analyzed by comparing ~15-s averages at 25% intervals throughout the fatiguing contraction. For each interval, the blood pressure signal was analyzed for the mean peaks [systolic blood pressure (SBP)], mean troughs [diastolic blood pressure (DBP)], and the number of pulses per second (multiplied by 60 to determine heart rate). MAP was calculated for each epoch with the following equation: MAP = DBP + 1⁄3(SBP – DBP).

Statistical Analysis

Data are reported as means ± SD within the text and displayed as means ± SE in the figures. Separate one-way ANOVAs (StatView, SAS Institute) was used to compare the time to task failure and percent decline in MVC torque between the men and women. Separate two-factor ANOVAs (sex × time) with repeated measures on time, were used to compare the dependent variables of heart rate, MAP, RPE, and SD of torque in the vertical and side-to-side directions. A three-factor ANOVA (sex × intensity × muscle) with repeated measures on intensity was used to compare the EMG-torque relation for the 6-s constant-torque contractions. Separate three-factor ANOVAs (sex × time × muscle) with repeated measures on time were used to compare the burst rate and AEMG during the fatiguing contraction. Because bursts were sometimes absent during a one-third interval of the time to task failure for some subjects, averages of the burst duration are reported and the results of independent t-tests are indicated where these analyses were possible. Post hoc analyses (Tukey-Kramer) were used to test for differences among pairs of means when appropriate. A significance level of $P < 0.05$ was used to identify statistical significance.

RESULTS

From the 31 men and women of varying strength who completed the experimental protocol (all-subjects group), 10 men and 10 women were matched for strength within 5% of maximal torque of the elbow flexor muscles (strength-matched group) (Fig. 2A). When several subjects could be matched for strength within the 5% criterion, those who were most similar in their reported physical activity levels were selected as a pair. The physical activity levels were similar for the men (134 ±
under the elbow was variable between subjects, the average forces did not differ throughout the fatiguing contraction for the men (46 ± 41 N) and women (59 ± 53 N) in the strength-matched group \((P > 0.05)\). Furthermore, there was no association between the time to task failure and the day of the menstrual cycle for the women \((r^2 = 0.09, P > 0.05)\).

**MAP and Heart Rate for Strength-Matched Subjects**

MAP increased during the fatiguing contractions \((P < 0.05)\) similarly for men and women \((P > 0.05\), Fig. 3A) in the strength-matched group. There was no difference in the MAP between men \((81 ± 8 \text{ mmHg})\) and women \((75 ± 8 \text{ mmHg})\) at rest and during the fatiguing contractions \((P > 0.05)\). The MAP was similar at the start of the contraction for men \((97 ± 12 \text{ mmHg})\) and women \((96 ± 15 \text{ mmHg}; P > 0.05)\) and at the time of task failure \((134 ± 18 \text{ and } 126 ± 26 \text{ mmHg}, \text{respectively}, \ P > 0.05)\). Consequently, the percent increase in MAP from rest until termination of the task was similar for the men \((72 ± 14\%); P > 0.05)\) and women \((67 ± 22\%); P > 0.05)\).

Heart rate also increased similarly throughout the fatiguing contraction \((P < 0.05)\) for the men and women. Men and women had a similar heart rate at rest \((70 ± 9 \text{ vs. } 68 ± 9 \text{ beats/min}; P > 0.05)\), the start of the contraction \((81 ± 12 \text{ vs. } 76 ± 9 \text{ beats/min}; P > 0.05)\), and at the time of task failure \((100 ± 13 \text{ vs. } 102 ± 17 \text{ beats/min}; P > 0.05)\) (Fig. 3B). Consequently, the percent change in heart rate from rest until termination of the task was similar for the men \((44 ± 16\%); P = 0.6)\) and women \((54 ± 35\%); P = 0.6)\).

**EMG-Torque Relation for the Strength-Matched Subjects**

The AEMG (% peak EMG) for the elbow flexor muscles was determined with isometric contractions held at 20, 40, and

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**Fig. 2.** Maximal voluntary contraction (MVC) torque of the strength-matched men and women. A: MVC torque of the pairs of men \((n = 10)\) and women \((n = 10)\) who were matched for strength within 5%. Line of identity indicates a perfect match. B: MVC torques (mean ± SE) before and immediately after the fatiguing contraction for the men and women in the strength-matched group. MVC torques were similar for men and women \((P > 0.05)\) and declined similarly by 31% after the fatiguing contraction.

**Fig. 3.** Mean arterial pressure (MAP; A) and heart rate (B) at rest and during the fatiguing contraction for men and women who were matched for strength. Values are means ± SE of 15-s intervals at 25% increments of the time to task failure. The increase in MAP and heart rate was similar for the men and women \((P > 0.05)\).

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106 MET·h/wk) and women \((102 ± 55 \text{ MET·h/wk}; P > 0.05)\) in the strength-matched group.

**MVC Torque**

The men \((n = 15; 74.4 ± 19.4 \text{ N·m})\) were stronger than the women \((n = 16; 60.4 ± 11.2 \text{ N·m})\) in the all-subjects group \((P < 0.05)\). However, MVC torque was similar for the men \((n = 10; 64.5 ± 8.7 \text{ N·m})\) and women \((n = 10; 64.5 ± 8.3 \text{ N·m})\) in the strength-matched group \((P > 0.05)\) (Fig. 2B). Furthermore, the MVC torque after the fatiguing contraction was reduced by a similar amount for the men and women in the strength-matched group \((31 ± 9\%; P > 0.05)\) (Fig. 2B).

**Time to Task Failure**

Each subject exerted a torque of 20% MVC during the fatiguing contraction. Because the MVC torque was similar for the men and women in the strength-matched group, target torque was similar for the two sexes \((12.6 ± 1.6 \text{ vs. } 12.8 ± 1.6 \text{ N·m}; P > 0.05)\). The time to task failure was similar \((P > 0.05)\) for the men \((819 ± 306 \text{ s})\) and women \((864 ± 391 \text{ s})\). In contrast, the women were weaker than the men in the all-subjects group, and the women \((1,024 ± 460 \text{ s})\) had a longer time to task failure compared with the men \((681 ± 328 \text{ s}; P < 0.05)\).

Neither the force exerted under the elbow during the fatiguing contraction nor the phase of the menstrual cycle for the women influenced the time to task failure. Although the force
60% MVC. AEMG increased with contraction intensity for all the elbow flexor muscles (P < 0.05) and was similar for the men and women (P > 0.05) at 20% (10.8 ± 4.9 vs. 10.6 ± 5.1%), 40% (26.3 ± 8.1 vs. 26.2 ± 8.9%), and 60% (47.4 ± 9.1 vs. 47.5 ± 14.7%) of MVC torque. However, the brachialis muscle had greater AEMG at the 20 and 40% target torques (16.6 ± 5.1 and 30.6 ± 10.4%, respectively) compared with the other elbow flexor muscles (9.3 ± 3.8 and 24.0 ± 7.9%) (P < 0.05) for both the men and women.

AEMG During the Fatiguing Contraction

The amplitude of the AEMG (% peak MVC) for each elbow flexor muscle of the strength-matched subjects increased during the fatiguing contraction (P < 0.05). However, the women had less AEMG throughout the fatiguing contraction (P < 0.05) and a reduced rate of increase in AEMG compared with the men as indicated by an interaction for sex and time (P < 0.05; Fig. 4). At the start of the contraction (first 30 s), the AEMG for all the elbow flexor muscles was 11.4 ± 4.7% for men and 10.9 ± 5.0% for women. At the end of the fatiguing contraction (last 30 s), the AEMG of all the elbow flexor muscles was 31.4 ± 10.3% for men and 24.0 ± 8.9% for women. The average rate of increase in AEMG, therefore, was 1.4%/min for the men and 0.92%/min for the women. In contrast, there was no main effect of muscle (P = 0.12) and no interaction for muscle and sex (P = 0.23) or time and muscle (P = 0.38). These results indicate that each of the elbow flexor muscles increased similarly during the fatiguing contraction for the two sexes, although there was a difference in the rate of increase for the men and women.

The AEMG of triceps brachii during the fatiguing contractions was substantially less than that for the elbow flexor muscles, but the average values increased during the fatiguing contractions from the start of the contraction (2.5 ± 2.0%) to task failure (3.7 ± 2.5%; P < 0.05; Fig. 4). This increase was similar for the strength-matched men and women (P > 0.05).

Bursts of EMG Activity During the Fatiguing Contraction

The fatiguing contractions were characterized by a progressive increase in the number of bursts in EMG activity, which corresponded to the transient recruitment of motor units. However, the burst rate was greater for the women compared with the men in the first third of the contraction (0.4 ± 0.7 vs. 0.1 ± 0.3 bursts/min), middle third (2.0 ± 2.1 vs. 1.3 ± 1.4 bursts/min), and last third of the contraction (5.6 ± 3.0 vs. 4.2 ± 2.8 bursts/min) (P < 0.05; Fig. 5). Correlation analysis, however, showed no significant association between the time to task failure and burst rate (r = 0.14; P > 0.05).

There was a main effect of muscle (P < 0.05) because the brachialis muscle (3.0 ± 3.9 bursts/min) had greater bursting activity than the short (2.1 ± 2.4 bursts/min) and long heads (1.6 ± 1.9 bursts/min) of biceps brachii. The brachioradialis (2.5 ± 2.8 bursts/min) also tended to display a greater burst rate than the long head of biceps brachii, but this did not reach statistical significance (P = 0.07). Although the EMG greater burst rate for the women appeared to be due to heightened activity in brachialis and brachioradialis, the interaction of muscle and sex did not reach statistical significance (P = 0.11), indicating that the burst activity in brachialis and brachioradialis was similar for the strength-matched men and women.
The purpose of this study was to compare the time to task failure for a submaximal fatiguing contraction sustained with the elbow flexor muscles by men and women who were matched for strength. The time to task failure was similar for the strength-matched men and women. Accordingly, there were no differences in the rates of increase in MAP and heart rate, RPE, fluctuations in torque during the fatiguing contraction, or the decline in MVC torque after the fatiguing contraction. Despite these similar performance characteristics, the pattern of EMG activity differed for the men and women: the women had less AEMG of the elbow flexor muscles during the contraction and at task failure for the surface and intramuscular EMG recordings, but they had a greater EMG burst rate during the fatiguing contraction.

**Time to Task Failure was Similar in Strength-Matched Men and Women**

Men and women who were matched for strength had similar times to task failure for a low-intensity contraction of the elbow flexor muscles. These findings are consistent with our previous observation of an association between the absolute target force and the time to task failure for the elbow flexor muscles (14). When the results of the two studies are pooled (n = 45), the exponential relation between target force and time to task failure was maintained (r = 0.78, $r^2 = 0.60$, P < 0.05) (Fig. 7), indicating that 60% of the variance in the time to task failure was explained by an exponential relation with the strength of the individual. When analyzed separately, both the women and men showed significant exponential relations between MVC force and time to task failure. However, the relation was stronger for the women (r = 0.76, $r^2 = 0.57$, P < 0.0001) compared with the men (r = 0.46, $r^2 = 0.22$, P =

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**Fig. 6.** SD of torque exerted at the wrist in the vertical (A) and side-to-side (B) directions during the fatiguing contraction. The mean (±SE) of the SD of torque is shown for the men and women for 30-s intervals at the beginning and 25, 50, 75, and 100% of the time to task failure. The SD of torque increased across the fatiguing contraction similarly for the strength-matched men and women in both the vertical and side-to-side directions (P < 0.05).

**DISCUSSION**

Correlation analysis was performed to determine the relation between the burst rate and rate of increase in EMG during the contraction for the men and women. There was no relation for the women (r = −0.07) or the men (0.10), nor when the sexes were pooled (r = −0.05).

The mean burst duration of EMG activity for the elbow flexor muscles during the fatiguing contractions was $4.6 \pm 2.2$ s. The mean burst duration was similar for the men and women ($4.9 \pm 2.7$ vs. $4.4 \pm 1.7$ s; P > 0.05) and did not change across the fatiguing contraction (P > 0.05). The burst duration was similar for all muscles (P > 0.05): short head of biceps brachii ($5.0 \pm 1.8$ s), long head of biceps brachii ($4.4 \pm 1.3$ s), brachioradialis ($4.7 \pm 2.6$ s), and brachialis ($4.6 \pm 3.0$ s).

**Fluctuations in Torque During the Fatiguing Contraction**

The amplitude of the fluctuations in torque (SD) in the vertical and side-to-side directions increased progressively during the fatiguing contraction (P < 0.05) for men and women. The fluctuations increased by $342 \pm 122\%$ from the first 30 s to the last 30 s of the fatiguing contraction for the vertical direction and by $569 \pm 480\%$ for the side-to-side direction. The increase in torque fluctuations during the contractions was not statistically different between men and women in the horizontal direction (P = 0.30, effect size = 0.37) and vertical direction (P = 0.14, effect size = 0.52; Fig. 6). However, the magnitude of these effect sizes is considered moderate for the vertical direction, suggesting a trend for women to have greater fluctuations near the time of task failure.

**RPE During the Fatiguing Contraction**

RPE was similar for men and women at the beginning and end of the fatiguing contraction (P > 0.05). The RPE values progressed from $1.1 \pm 0.9$ at the start of the contraction to $5.4 \pm 1.8$ at 25% of time to task failure, $8.2 \pm 1.2$ at 50% of time to task failure, $9.5 \pm 0.8$ at 75% of time to task failure, and $10 \pm 0.1$ at task failure.

Fig. 7. Exponential relation between maximal strength and time to task failure for a sustained submaximal contraction at 20% of MVC force with the elbow flexor muscles for men and women. The individual data points represent the data from this study (n = 31) and a previous study (14) (n = 14).
0.03). These differences are attributable to the strength of the subjects, which ranged from 130 and 550 N. The strength of the men, which ranged from 200 to 550 N, was located on the plateau of the relation for the time to task failure where there was a relatively weak relation with muscle strength. A linear regression analysis suggested a breakpoint in the relation at ~240 N, which may correspond to a threshold above which there was an occlusion of blood flow during the fatiguing contraction. Conversely, the strength of the women (130–300 N) placed them on the steep portion of the relation. Certainly, the relation between strength and perfusion has been demonstrated for the handgrip muscles (1), although not during a fatiguing contraction. Consequently, the mechanism for the longer time to task failure for a submaximal sustained contraction performed with the elbow flexor muscles (14, 18, 27, 30) in both sexes, but especially women, is largely influenced by the absolute force exerted during the contraction and likely involves muscle perfusion.

However, the absolute-force explanation cannot account for differences in the time to task failure for all muscles and tasks. Our results are consistent with studies that have shown a significant association between strength and time to task failure for the tibialis anterior and back extensor muscles when men are stronger than women (4, 19). Similarly, women experienced less muscle fatigue than men when performing intermittent maximal contractions with the tibialis anterior muscle, but fatigue was similar for the two sexes when blood flow to the muscle was occluded (29). In contrast, there are reports of no association between the initial strength and time to task failure for a sustained low-intensity contraction with the handgrip muscles (35) and the knee extensor muscles (22), despite a longer time to task failure of the women compared with the men. Furthermore, women had a longer time to task failure for a moderate-intensity intermittent contraction of the adductor pollicis when matched for strength with men (7). Consequently, factors other than differences in strength also contribute to task termination of a sustained contraction for men and women. Other mechanisms proposed to account for the sex difference in muscle fatigue have included differences in substrate utilization, muscle morphology, and neuromuscular activation (12). Taken together, the sex difference in the time to task failure is dependent on the muscle involved, the type and intensity of the contraction, and the details of the task that is performed. However, for a low-intensity contraction sustained with the elbow flexor muscles, the primary mechanism responsible for the sex difference appears to be related to the absolute strength exerted during the contraction.

Pressor Response Was Similar in Strength-Matched Men and Women

The pressor response indicated the cardiovascular adjustments that occurred during the fatiguing contraction. The strength-matched men and women exhibited a similar pressor response during the fatiguing contraction, which suggests that they likely experienced similar magnitudes of intramuscular pressure on the feed arteries, similar magnitudes of blood occlusion, and therefore a similar metaboreflex. These findings support previous findings that women were able to sustain a longer time to task failure of a low-force contraction due to differences in muscle strength that influenced muscle perfusion (14). These results are also consistent with studies that have shown an association between the pressor response and the time to task failure with the amount of muscle mass that is activated during a sustained isometric contraction (8, 25, 31, 32). Conversely, elimination of muscle perfusion as a factor, which occurs during ischemic contractions, will eliminate the sex difference in muscle fatigue, as was observed for high-force contractions with the tibialis anterior muscle (29). Consequently, attempts by the central nervous system to maintain muscle perfusion were similar for the strength-matched men and women.

EMG Activity Differed for Strength-Matched Men and Women

Although the AEMG increased during the fatiguing contraction, the average rate of increase was less for the women in the strength-matched group. The lesser EMG activity used by the women was not due to the women ending the task prematurely: the magnitude of reduction in MVC torque was similar at task failure for the two sexes, and they had similar rates of rise in RPE and heart rate. The difference in the increase in EMG was also not due to recording conditions because there was no difference between the two sexes in the EMG-force relation obtained in the unfatigued state and the same difference was observed with surface and intramuscular (brachialis) electrodes. Therefore, the lesser EMG for the women was due either to 1) a greater magnitude of cancellation in the recorded EMG signal (Ref. 5; Farina D, Merletti R, and Enoka RM, unpublished observations) during the fatiguing contraction; 2) a lesser activation of the muscle by the spinal cord during the sustained contraction; or 3) a greater reliance of the transient recruitment of motor units. The excitatory descending drive to the motor neuron pool appeared to be similar because the rates of increase in perceived effort (RPE), torque fluctuations, and heart rate were similar for the men and women and all are mediated by descending drive (3, 10, 23). These data do not indicate how the women were able to sustain the same force for a comparable duration with lesser average EMG.

One possibility is that the bursting activity of the interference EMG, which represents a transient increase in motor unit recruitment (15, 20, 34), may indicate a difference in the reliance on phasic motor unit activity. The women had a greater rate of bursting activity, despite a lesser AEMG and similar time to task failure compared with the men. Consequently, the women showed a greater use of the transient activation of motor units, perhaps including motor unit substitution (36), rather than a progressive increase in motor unit recruitment that is indicated by the increase in AEMG (6, 11). Although the brachialis and brachioradialis showed greater bursting activity than the long and short heads of biceps brachii, this was the case for both the men and women, indicating there was no preferential bursting in the synergist muscles of the elbow flexor muscles for the women compared with the men. Greater EMG burst activity was also observed in women after a period of limb immobilization, although the burst activity was not quantified and the time to task failure was longer in the women (33). Furthermore, a reduction in the bursting activity in the EMG was associated with a longer time to task failure for a force task after practice of a fatiguing contraction (15) and in women compared with men (17).
However, the association ($r = 0.14$) between time to task failure and burst rate in the present study was not significant ($P > 0.05$), indicating that the bursting activity was dependent on the rate of increase in EMG activity for both men and women.

The transient increase in recruitment of motor units did not result in larger fluctuations of motor output: the torque fluctuations were statistically similar for the men and women, although there was a trend for women to have greater fluctuations in the vertical direction near task failure. These results suggest that the mechanisms contributing to the fluctuations in torque and bursting activity are likely to differ, although their origin is similar in men and women.

In summary, men and women who were matched for strength had a similar pressor response and time to task failure for a sustained contraction of the elbow flexor muscles. These results indicate that strength-matched men and women experienced similar cardiovascular adjustments during the fatiguing contraction. However, the EMG activity for the elbow flexor muscles (including the increase in the average EMG and EMG bursting activity) differed between the sexes. Consequently, the men and women achieved a similar performance with varying strategies for activating the motor neuron pool. Thus men and women of equal strength experienced similar levels of muscle fatigue when performing a submaximal isometric contraction. Thus men and women who were matched for strength and endurance of the elbow extensor muscles (including the increase in the average EMG and EMG bursting activity) differed between the sexes. Consequently, the men and women achieved a similar performance with varying strategies for activating the motor neuron pool. Thus men and women of equal strength experienced similar levels of muscle fatigue when performing a submaximal isometric contraction.

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