Influence of aging on sex differences in muscle fatigability

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Hunter, Sandra K., Ashley Critchlow, and Roger M. Enoka. Influence of aging on sex differences in muscle fatigability. J Appl Physiol 97: 1723–1732, 2004.—The purpose of this study was to compare time to task failure for a sustained isometric contraction performed at a submaximal intensity with elbow flexor muscles by young and old men and women. Twenty-seven young (14 men and 13 women, 18–35 yr) and 18 old (10 men and 8 women, 65–80 yr) adults sustained an isometric contraction at 20% of maximal voluntary contraction torque until target torque could no longer be achieved for ≥5 s. Young adults were stronger than old adults (66.8 ± 17.9 vs. 47.7 ± 18.1 N·m, P < 0.05), and men were stronger than women (69.8 ± 17.9 vs. 47.1 ± 15.3 N·m, P < 0.05), with no interaction between age and sex (P > 0.05). Time to task failure was longer for old than for young adults (22.8 ± 9.1 vs. 14.4 ± 7.6 min, P < 0.05) and for young women than for young men (18.3 ± 8.0 vs. 10.8 ± 5.2, P < 0.05), but there was no difference between old women and men (21.3 ± 10.7 and 24.1 ± 8.0 min, respectively, P > 0.05) or between young women and old adults (P > 0.05). Mean arterial pressure, heart rate, average electromyographic (EMG) activity, and torque fluctuations of elbow flexor muscles increased during the fatiguing contraction (P < 0.05) for all subjects. Rates of increase in mean arterial pressure, heart rate, and torque fluctuations were greater for young men and old adults, with no differences between old men and women (P > 0.05). Similarly, the rate of increase in EMG activity was greater for young men than for the other three groups. EMG bursts were less frequent for old adults (P < 0.05) at the end of the fatiguing contraction, and this was accompanied by reduced fluctuations in torque. Consequently, time to task failure was related to target torque for young, but not old, adults, and differences in task duration were accompanied by parallel changes in the pressor response.

Young women are capable of longer-duration contractions than young men when performing sustained submaximal isometric contractions to task failure at low-to-moderate intensities (19). This sex difference is observed for several muscle groups, including adductor pollicis (11), elbow flexors (24, 26), extrinsic finger flexors (36, 45), back extensors (9), and knee extensors (33). The difference in time to task failure for sustained contractions, but not submaximal intermittent contractions (16), performed by young adults is partially explained by differences in strength (21, 24). When men are stronger than women, the women are able to sustain a contraction for a longer duration before failure of the task, and the increase in mean arterial pressure (MAP, pressor response) is less for women (24). When men and women are matched for strength, however, the time to task failure and the pressor response are similar (21). The pressor response is the reflex-mediated increase in MAP during an isometric fatiguing contraction primarily due to accumulation of metabolites in the muscle and a heightened metaboreflex (34, 38). These results are consistent with the hypothesis that men, who are usually stronger than women and sustain greater absolute forces when the contraction is performed at a relative intensity, experience increased intramuscular pressures, greater blood flow occlusion, increased accumulation of metabolites and impairment of oxygen delivery to the muscle (2, 40, 41), and an earlier onset of task failure during a sustained contraction. Consistent with these results, Russ and Kent-Braun (39) found that the sex difference in muscle fatigue for maximal contractions was eliminated when blood flow to the muscle was occluded.

Because aging is accompanied by substantial reductions in muscle mass and strength (27, 29, 32), weaker old adults should be able to sustain a relative submaximal force for a longer duration than young adults. A similar relation should exist when blood flow to the muscle was occluded. The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

METHODS

Twenty-seven young adults (14 men and 13 women, 18–35 yr old) and 18 old adults (8 women and 10 men, 65–80 yr old) volunteered to participate in the study. All subjects were healthy, with no known...
neurological or cardiovascular diseases, and were naive to the protocol. Before participation in the study, each subject provided informed consent, and the Human Subjects Committee at the University of Colorado approved the protocol.

The physical activity level for each subject was assessed with a questionnaire (31) that estimated the relative kilocalorie expenditure of energy per week. Arm dominance was estimated using the Edinburgh Handedness Inventory (35); all subjects were right handed. The day of the menstrual cycle on which the experimental protocol was performed was recorded for each young female participant; all young women had a normal menstrual cycle. The 1st day of menstruation was considered day 1 of the cycle. None of the old women were on hormone replacement therapy, and all had been postmenopausal for >10 yr.

**Mechanical Recording**

Subjects were seated upright in an adjustable chair with the nondominant arm abducted slightly and the elbow resting on a padded support. The elbow joint was extended and the force at the wrist was directed upward when the elbow flexor muscles were activated during a voluntary contraction. 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 using a Power 1401 analog-to-digital (A-D) converter and Spike2 software (Cambridge Electronics Design, 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). The insulation of one wire in each pair was 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 antecebral 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 a computer using the Power 1401 A-D converter (Cambridge Electronics Design) 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**

Each subject visited the laboratory for 1) an introductory session for familiarization with the equipment and performance of maximal voluntary contractions (MVC) and 2) one experimental session. The protocol consisted of 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 (17). 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.

**EMG activity.** The EMG activity of the involved muscles was recorded in standardized tasks so that the EMG-torque relation could be compared between young and old men and women in the nonfatigued state. The subject performed a sustained constant-torque contraction with the elbow flexor muscles for 6 s at target values of 20, 40, and 60% MVC. The subject was allowed 30 s of rest between contractions. These relations for the groups of subjects were examined to ensure 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 (5). 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 online using a Power 1401 A-D converter (Cambridge Electronics Design) and analyzed offline using the Spike2 data-analysis system (Cambridge Electronics Design). 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% 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 direction as the coefficient of variation for torque (SD/mean × 100) 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 task duration. Frequency analysis was performed on force using a modified Welch’s periodogram method with a Hanning window (no overlap) that had the same size as the fast Fourier transform (256 points). The resolution of the power spectra for the original force was 1.95 Hz. The mean force was subtracted from each signal during the analysis. Frequency analysis was performed on the force for 30-s intervals at the start, middle, and end of the fatiguing contraction. The analyses determined the percentage of the total power in the frequency bin, the maximal power, the frequency at the maximal power, and the median frequency.

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 (21, 23, 25, 26). 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 average of the rectified EMG 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 SD above the mean of the smoothed, differentiated EMG signal. The 3-SD criterion was based on EMG records from fatiguing 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 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 a second burst was constrained to be >2 s from the previous burst, and the minimal 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 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

Values are means ± SD in RESULTS and Tables 1 and 2 and means ± SE in Figs. 1–8. Separate analyses of variances (ANOVA, SPSS version 11.0) were used to compare the time to task failure and percent decline in MVC torque between the old and young men and women. Separate three-factor ANOVAs (age × sex × time) with repeated measures on time were used to compare the dependent variables of heart rate, MAP, RPE, and coefficient of variation (CV) of torque. A four-factor ANOVA (age × sex × intensity × time) with repeated measures on intensity was used to compare the EMG-torque relation for the 6-s constant-torque contractions. Separate four-factor ANOVAs (age × 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 one-third 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. Independent t-tests were used to test for differences among pairs of means when appropriate; Bonferroni’s correction for statistical significance was used in these instances. Associations were determined between some variables using Pearson’s correlation analysis. P < 0.05 was used to identify statistical significance.

RESULTS

The physical activity levels were similar for the men and women [84 ± 51 and 80 ± 84 metabolic equivalents (MET)·h⁻¹·wk⁻¹, respectively, P > 0.05] within the age groups, but the old adults were less active than the young adults (47 ± 38 vs. 107 ± 76 MET·h⁻¹·wk⁻¹, P < 0.05; Table 1).

MVC Torque and Time to Task Failure

The young adults were stronger than the old adults (P < 0.05), and the men were stronger than the women (P < 0.05; Table 1), with no interaction between age and sex (P > 0.05). The MVC torque after the fatiguing contraction was reduced (P < 0.05) by 32% for the young and old adults and for the men and women (P > 0.05; Table 1).

Each subject exerted a torque of 20% MVC during the fatiguing contraction. The time to task failure was longer for the old than for the young adults (22.8 ± 9.1 vs. 14.4 ± 7.6 min, P < 0.05). An interaction between sex and age (P < 0.05) indicated a sex difference for the young adults, but not for the old adults: time to task failure was shorter for the young men than for the young women (10.8 ± 5.2 vs. 18.3 ± 8.0 min), but the task duration was similar for the old men and women (24.1 ± 8.0 and 21.3 ± 10.7 min, respectively; Fig. 1). Furthermore, there was no difference in time to task failure between the young women and old adults (P > 0.05). Consistent with these findings, the time to task failure was inversely related to target torque for the young adults (r² = 0.54, P <

Table 1. Age, physical activity level, MVC torque before fatiguing contraction, and percent decline in MVC torque after fatiguing contraction

<table>
<thead>
<tr>
<th>Young</th>
<th>Old</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Men</td>
</tr>
<tr>
<td>Age, yr</td>
<td>22 ± 4</td>
</tr>
<tr>
<td>Physical activity, MET·h⁻¹·wk⁻¹</td>
<td>109 ± 98</td>
</tr>
<tr>
<td>Before, N=m</td>
<td>76 ± 19</td>
</tr>
<tr>
<td>After, %decline</td>
<td>33 ± 6</td>
</tr>
</tbody>
</table>

Values are means ± SD. MET, metabolic equivalents. There was a main effect of age (*P < 0.05), physical activity, and maximal voluntary contraction (MVC) torque (before) between young and old adults. Decline in MVC torque (after) was similar for the 4 age groups. There was no main effect for sex or any interactions with age.
Time to task failure was longer in old adults ($P < 0.05$). There was an effect of sex ($P < 0.05$) for young, but not old, adults.

These relations were similar for the young adults ($r^2 = 0.53$, $P < 0.05$) but not the old adults ($r^2 = 0.01$, $P > 0.05$) when time to task failure was correlated to the force exerted at the wrist.

The young adults exerted a greater average force under the elbow during the fatiguing contraction than the old adults (46.6 ± 40.2 vs. 16.8 ± 16.9 N, $P < 0.05$). The change in elbow force during the task was described by a quadratic function, indicating that the force initially increased and then decreased toward the end of the fatiguing contraction. An interaction between age and time ($P < 0.05$), however, indicated that the increase in elbow force was due to the young adults, inasmuch as the elbow force did not change for the old adults. There was no main effect for sex, and there were no interactions between sex and age ($P < 0.05$) or sex and time, which indicated that the women and men within each age group exerted a similar force under the elbow joint during the fatiguing contraction. Furthermore, there was no correlation between time to task failure and elbow force ($r = -0.24$, $P = 0.12$). Collectively, these results indicate that although old adults exerted less force under the elbow during the fatiguing contraction, this difference was not related to differences in time to task failure.

The phase of the menstrual cycle for the young women did not influence the time to task failure. There was no association between the time to task failure and the day of the menstrual cycle for the women ($r^2 = 0.02$, $P > 0.05$). All the old women were postmenopausal, and none were taking hormone replacement therapy.

**RPE During the Fatiguing Contraction**

RPE increased during the fatiguing contraction ($P < 0.05$) but was similar for old and young men and women at the beginning and end of the fatiguing contraction ($P > 0.05$). RPE progressed from 1.3 ± 0.1 at the start of the contraction to 5.9 ± 0.3 at 25% of time to task failure, 8.1 ± 0.2 at 50% of time to task failure, 9.4 ± 0.1 at 75% of time to task failure, and 10 ± 0.1 at task failure. There were no main effects for age or sex and no interactions with time ($P > 0.05$). However, the rate of increase in RPE was more gradual for the old adults because of the longer duration of the contraction. Similarly, the rate of rise in RPE was slower for the young women than for the young men, but the rate of increase was similar for the old men and women.

**MAP and Heart Rate**

MAP increased during the fatiguing contractions ($P < 0.05$) for the young and old adults (Fig. 3A). There was a main effect for sex due to the lower MAP for the women throughout the fatiguing contraction ($P = 0.05$). An interaction between age and sex indicated that the rate of rise in MAP was greater ($P < 0.05$) for the young men than for the young women (5.2 ± 0.5 vs. 2.0 ± 0.1 mmHg/min) but similar in the old men and women (1.8 ± 0.9 and 2.4 ± 1.6 mmHg/min, respectively). At task failure, MAP was lower in the young women was lower than in the young men (123 ± 18 vs. 139 ± 18 mmHg, $P < 0.05$); however, the terminal values were similar for the old men and women (140 ± 12 and 134 ± 22 mmHg, respectively, $P > 0.05$).

Heart rate also increased during the fatiguing contraction for all subjects ($P < 0.05$; Fig 3B). There was a main effect for age ($P < 0.05$) because of a greater increase in heart rate during the fatiguing contraction and a greater heart rate at termination of the task for the young adults. The young adults increased heart rate at 2.7 ± 3.3 beats/min compared with 0.9 ± 0.7 beats/min for the old adults. Heart rate was greater for the young men than for the young women ($P < 0.05$) but was similar for the old men and women ($P > 0.05$).
nounced at the lower torques. AEMG was also greater for old than for young adults ($P < 0.05$) at each contraction intensity, but this was due to greater activity of the brachialis muscle for the old women ($P < 0.05$).

**AEMG During the Fatiguing Contraction**

The amplitude of the AEMG (%peak EMG) for each elbow flexor muscle increased during the fatiguing contraction for all four groups of subjects ($P < 0.05$; Fig. 4). However, AEMG was greater for the old than for the young adults during the fatiguing contractions (25.1 ± 15.9 vs. 17.4 ± 9.0%, $P < 0.05$). This age effect was specific to the old women; their AEMG values were greater than those of the old men (28.3 ± 18.7 vs. 21.8 ± 12.7%) across the fatiguing contraction ($P < 0.05$), but the converse relation was observed for the young men and women (18.6 ± 9.9 and 16.2 ± 7.8%, respectively). The rate of increase in AEMG was greater for the young men than for the young women: the men and women began at similar AEMG values (11.5 ± 4.9 and 9.7 ± 4.0%, respectively), but the increase at the termination of the task was greater for the young men than for the young women (29.2 ± 10.2 vs. 23.6 ± 8.9%). In contrast, rates of rise in AEMG were similar for old men and women, although the old women started and ended (19.3 ± 20.5 and 37.9 ± 22.8%, respectively) the fatiguing contraction at higher levels than the old men (13.7 ± 8.9 and 31.7 ± 14.1%, respectively).

The AEMG differed across muscles ($P < 0.05$; Fig. 5). The average AEMG for brachialis (28.4 ± 16.4%) was greater ($P < 0.05$) than that for the short (16.8 ± 10.2%) and long heads of biceps brachii (19.9 ± 10.2%) and brachioradialis (19.8 ± 11.4%). This difference was attributable to the brachialis muscle of the old women (Fig. 5D), as indicated by an interaction among age, sex, and muscle ($P < 0.05$). The AEMG of the triceps brachii muscle increased from the start of the fatiguing contraction (3.2 ± 1.9%) to task failure (4.9 ± 2.6%, $P < 0.05$). However, AEMG of the triceps brachii muscle was substantially less than AEMG of the elbow flexor muscles, and the rate of rise was similar for men and women for young and old adults (Fig. 5; $P > 0.05$).

**EMG-Torque Relation**

AEMG (%peak EMG) for the elbow flexor muscles was determined during isometric contractions held at 20, 40, and 60% MVC. AEMG increased with contraction intensity for the young and old men and women ($P < 0.05$; Table 2). AEMG of the brachialis muscle was significantly greater than AEMG of the other elbow flexor muscles for the young and old men and women ($P < 0.05$), although the difference was more pro-

**Table 2. Relation between average EMG and torque for elbow flexor muscles**

<table>
<thead>
<tr>
<th>Target torque</th>
<th>Young Men</th>
<th>Young Women</th>
<th>Old Men</th>
<th>Old Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>20% MVC</td>
<td>11.3±2.8</td>
<td>10.5±2.0</td>
<td>13.7±5.0</td>
<td>17.4±5.2*</td>
</tr>
<tr>
<td>40% MVC</td>
<td>28.9±6.0</td>
<td>25.2±5.8</td>
<td>28.0±7.9</td>
<td>32.9±8.1*</td>
</tr>
<tr>
<td>60% MVC</td>
<td>51.9±8.9</td>
<td>46.4±8.7</td>
<td>50.1±9.1</td>
<td>55.9±9.2*</td>
</tr>
</tbody>
</table>

Values are means ± SD of average rectified EMG normalized to peak EMG during MVC for each of the 4 elbow flexor muscles pooled. *$P < 0.05$ compared with the other 3 groups of subjects.

![Fig. 3. Mean arterial pressure (MAP; A) and heart rate (B) during fatiguing contraction for young and old men and women. Values are means ± SE of 15-s intervals at 25% increments of time to task failure. Increase in MAP and heart rate was similar for old men and women ($P > 0.05$) but greater for young men than for young women ($P < 0.05$).](image)

![Fig. 4. Average rectified EMG (AEMG) of elbow flexor muscles throughout fatiguing contraction for young and old men and women. Each data point represents mean AEMG amplitude for 1% of time to task failure for elbow flexor muscles pooled with every second 1% interval plotted. Rate of increase in AEMG was greater for young men than for the other 3 groups, and average AEMG during the task was greater for young men than for young women and for old women than for old men ($P < 0.05$).](image)
Bursts of EMG Activity During the Fatiguing Contraction

There was a progressive increase in the number of bursts in EMG activity during the fatiguing contraction ($P < 0.05$), which corresponded to the transient recruitment of motor units. The burst rate was greater ($P < 0.05$) for the young than for the old adults in the first third (0.2 ± 0.5 vs. 0.0 ± 0.2 bursts/min), middle third (1.7 ± 1.7 vs. 0.2 ± 0.4 bursts/min), and last third (5.0 ± 2.8 vs. 1.4 ± 1.8 bursts/min) of the contraction. An interaction between age and time ($P < 0.05$) indicated that the difference due to age increased in the second and last thirds of the task (Fig. 6). Correlation analysis indicated a significant, but modest, negative association between the time to task failure and burst rate ($r^2 = -0.12$, $P < 0.05$).

The increase in the EMG burst rate was similar for men and women ($P = 0.84$), and there were no interactions between sex and age ($P = 0.18$) or sex and time ($P = 0.28$; Fig. 6). There was a main effect for muscle ($P < 0.05$), however, and a muscle × time interaction ($P < 0.05$) due to a lower burst rate in the last third of the task for the long head of biceps brachii (2.8 ± 2.3 bursts/min) than for the short head of biceps brachii (3.3 ± 2.5 bursts/min), brachialis (3.8 ± 4.1 bursts/min), and brachioradialis (4.3 ± 2.6 bursts/min) muscles. There were no interactions for muscle and time with sex or age.

Fluctuations in Torque During the Fatiguing Contraction

The normalized amplitude of the vertical fluctuations in torque (CV) increased by 160 ± 97% from the first 30 s to the last 30 s of the fatiguing contraction for the young men and women ($P > 0.05$) and for the young and old (4.9 ± 1.4 and 5.5 ± 3.6 s, respectively) adults ($P > 0.05$). There was no interaction between sex and time ($P > 0.05$). The burst duration did not change during the contraction for any group and was similar for all muscles ($P > 0.05$): short head of biceps brachii (5.3 ± 3.0 s), long head of biceps brachii (5.6 ± 7.3 s), brachioradialis (4.4 ± 2.0 s), and brachialis (5.2 ± 5.0 s).
torque fluctuations was similar for the old men and women ($P < 0.05$) but greater for the young men than for the young women ($P < 0.05$). There was a positive association between the increase in CV for torque and the burst rate of EMG ($r^2 = 0.32, n = 45, P < 0.05$, muscles pooled), indicating that 32% of the increase in fluctuations was explained by the increase in EMG burst rate.

Most of the changes in CV for torque were explained by changes in the absolute total power of the density spectra for force ($r^2 = 0.55, n = 45, P < 0.05$). The peak of the power density spectrum for force occurred in the 0- to 4-Hz range at the start ($2.3 \pm 2.6$ Hz) and end ($2.2 \pm 1.0$ Hz) of the fatiguing contraction ($P > 0.05$), and the median frequency, collapsed across groups, did not change ($P = 0.14$) from the start ($3.0 \pm 2.9$ Hz) to the end ($2.4 \pm 1.1$ Hz) of the task (Fig. 8). The power in the 2- to 4-Hz bin was $43 \pm 8\%$ of the total power at the start of the contraction and $46 \pm 9\%$ at the end of the contraction ($P < 0.05$). There was also a secondary peak around $18–20$ Hz for the young and old adults at the start of the contraction ($6.1 \pm 8.7\%$ of total power), although this peak had disappeared by the end of the contraction ($0.8 \pm 1.7\%$). Consequently, there was a shift in the distribution of power to lower frequencies during the fatiguing contraction ($P < 0.05$). The shift was greatest for the women (interaction among frequency, time, and sex); the young and old women had a larger peak power than the men at the end of the contraction but a similar peak at the start of the contraction. There was no interaction among frequency, time, sex, and age ($P = 0.3$), indicating that the change in power distribution was similar for the young and old women across the frequency bins. However, there was an interaction among frequency, time, and sex due to the similar amount of power at $0–4$ Hz for the old adults at the start and end of the contraction, whereas there was a shift for the young adults to higher values when the men and women were pooled. The old women, however, experienced a large shift in power to $0–4$ Hz, whereas the old men increased power at $5–10$ Hz (Fig. 8D).

**DISCUSSION**

The purpose of this study was to compare the time to task failure for a sustained isometric contraction performed at a submaximal intensity with the elbow flexor muscles by young

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**Fig. 7.** Fluctuations in torque in the vertical direction were quantified as coefficient of variation (CV) for torque exerted at the wrist. CV of torque is shown for young and old men and women for 30-s intervals at the beginning and 25, 50, 75, and 100% of time to task failure. Values are means ± SE.

**Fig. 8.** Percent power at different frequencies in the force signal during fatiguing contraction at the start (first 30 s, A and C) and end (last 30 s, B and D) of fatiguing contraction for young (A and B) and old (C and D) adults. Values are means ± SE.
and old men and women. The main finding was that the time to task failure was longer for the young women than for the stronger young men and for the old adults than for the stronger young adults but similar for the old men and women, despite the old men being stronger. Consequently, there was an inverse relation between the target torque and the time to failure for the contraction at 20% MVC torque for the young, but not the old, adults. The main effect for age was accompanied by reduced rates of increase in MAP, heart rate, RPE, force fluctuations, and EMG bursts, but not average changes in EMG activity or the frequency distribution in the force.

The differences in time to task failure among the groups were not due to differences in motivation or relative performance: 1) the decline in maximal strength recorded after task failure was similar for the young and old men and women, and 2) the effort exerted during the contraction and at task failure was similar across groups (indicated by the RPE).

The rate of increase in MAP was greater for the young men than for the other three groups, who exhibited a similar rate of increase (Fig. 3A), and MAP at task failure was lower for the young women than for the young men and old adults. The more gradual increase in MAP for the young women than for the young men is consistent with previous findings for a sustained submaximal contraction (21, 24, 26), which suggested that the sex difference in task duration for young adults was explained by the target torque and its influence on the blood supply to the muscle (39). Furthermore, the rate of increase in MAP was similar for the young women and both groups of old adults and consistent with the similar time to task failure for the three groups. Similarly, the rate of increase in heart rate was less for the young women than for the young men but similar for the old men and women (Fig. 3B). The lower heart rate exhibited by the old adults at task failure and during the contraction may be explained by the decline in maximal heart rate with advancing age (14).

Although the old men were stronger than the old women, the time to task failure and the rates of increase in MAP and heart rate were similar for the old men and women. Similar associations were reported previously when old adults performed a series of submaximal intermittent contractions with a hand muscle (7). Some other mechanism independent of the absolute force exerted during the contraction must be responsible for determining the time to task failure for the old adults, in contrast to the relations observed for young adults. One possible mechanism is the greater area of type I fibers (28, 32) and the associated increased oxidative capacity that has been observed in old adults (30), which would result in a reduced metaboreflex and longer time to task failure for a contraction at the same relative intensity. Although alterations in fiber type area might account for the longer time to task failure for the old than the young adults, this mechanism may not explain the similar task duration for the old men and weaker old women, unless the old men had even greater changes in motor unit properties than the old women. Alternatively, a sex hormone mechanism may have been responsible for the difference in time to task failure; estrogen is not implicated, because time to task failure was similar for the young and old women, and the old women were postmenopausal and had not been chronically exposed to circulating estrogens for ≥10 yr. These results are consistent with those for a submaximal intermittent task, where no differences in time to failure were observed between women who were taking hormone replacement therapy and those who were not (7). Hence, the briefer time to task failure for the young men than for the other three groups must be mediated by some characteristic of the young men.

As with the adjustments in MAP, the rate of increase in EMG activity was greater for the young men than for the other three groups of subjects. Because the increase in AEMG during a fatiguing contraction largely reflects the increases in motor unit recruitment (6, 12, 18, 37), the young men presumably had a greater rate of recruitment as the already active fibers progressively fatigued. Furthermore, the transient recruitment of motor units, as indicated by the EMG burst analysis (22), increased more rapidly for the young men. Despite the similar rate of increase in EMG activity for the young women and the two groups of old adults, the relative increase in EMG amplitude at task failure was less for the young women (Fig. 4). These results suggest that the young women may have experienced greater fatigue-associated alterations in the muscle fiber action potentials, which can occur with long-duration contractions (15) and result in greater cancellation of the recorded EMG (13). Although the rate of increase in EMG was similar for the young women and the two groups of old adults, the young women increased the transient recruitment of motor units more rapidly and to a greater extent than the old adults (Fig. 6), which likely contributed to an earlier termination of the task. Interestingly, the greater reliance on the brachial muscle by the old women than by the old men had no significant influence on the time to task failure.

The differences in EMG activity among the four groups of subjects were underscored by the changes in the torque fluctuations. Because the amplitude of the fluctuations increases with the intensity of the contraction (8, 10), the different rates of rise in the normalized fluctuations indicate that the adjustments in muscle activity differed among the groups. Accordingly, the rate of increase in the torque fluctuations was greatest for the young men, intermediate for the young women, and similar for the two groups of old adults (Fig. 7). In combination, the changes in average EMG activity, EMG bursts, and torque fluctuations suggest that the increase in motor unit activity, which ultimately limits task duration, was most rapid for the young men and most gradual for the old adults.

The force was examined in the frequency domain during the fatiguing contraction to compare the adjustments made by young and old men and women. As expected from the increase in the fluctuations, there was an increase in power of the force signal between the start and the end of the contraction. At the start of the fatiguing contraction, the force was dominated by frequencies of ~1–4 Hz for the young and old men and women, with a secondary, but smaller, peak at ~20 Hz. The dominance of the 1- to 4-Hz power of the force is common and attributed to low-frequency modulation of the motor unit discharge (42–44). The 20-Hz peak at the start of the fatiguing contractions may be attributable to mean discharge rate of the motor units (43). The 20-Hz peak was reduced with fatigue, and the power and percent power increased at the lower frequency range (1–4 Hz), particularly for the women. The greater shift to lower frequencies of oscillation with fatigue was not associated with the sex differences in time to task failure, because the shifts were greater for the young and old women than for the men, but the sex difference in time to task failure was less for the young women and the two groups of old adults, the relative increase in EMG amplitude at task failure was less for the young women (Fig. 4). These results suggest that the young women may have experienced greater fatigue-associated alterations in the muscle fiber action potentials, which can occur with long-duration contractions (15) and result in greater cancellation of the recorded EMG (13). Although the rate of increase in EMG was similar for the young women and the two groups of old adults, the young women increased the transient recruitment of motor units more rapidly and to a greater extent than the old adults (Fig. 6), which likely contributed to an earlier termination of the task. Interestingly, the greater reliance on the brachial muscle by the old women than by the old men had no significant influence on the time to task failure.

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failure was observed only for the young women. There was no interaction among frequency, time, sex, and age, indicating that the change in power distribution was similar for the young and old women across the frequency bins. Nevertheless, the shifts in power to lower frequencies were greater for the young women than for the old men, indicating differences in force modulation that were independent of strength and time to task failure. Consequently, these results indicate that there are fundamental differences in the modulation of motor output with muscle fatigue between men and women and between young and old adults.

In summary, the time to task failure for a submaximal contraction with the elbow flexor muscles was longer for old than for young adults, but this effect was due to a shorter duration for the young men. Consequently, there was a sex difference in performance for the young, but not the old, adults, despite a comparable difference in strength between the two sexes. Measurements of MAP, heart rate, RPE, EMG activity, and fluctuations in torque suggest that motor unit activity increased most rapidly during the fatiguing contraction for the young men and at the lowest rates for the old adults. Some other mechanisms that do not involve contraction strength must contribute to the reduced pressor response and similar time to task failure for the old men and women.

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REFERENCES


