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Skeletal muscle fatigue, strength, and quality in the elderly: the Health ABC Study

Andreas Katsiaras, Annette B. Newman, Andrea Kriiska, Jennifer Brach, Shanthi Krishnaswami, Eleanor Feingold, Stephen B. Kritchevsky, Rongling Li, Tamara B. Harris, Ann Schwartz, and Bret H. Goodpaster.

Division of Endocrinology and Metabolism, Department of Medicine, University of Pittsburgh, Pittsburgh; Department of Epidemiology, Graduate School of Public Health, University of Pittsburgh, Pittsburgh; Graduate School of Public Health, University of Pittsburgh, Pittsburgh, Pennsylvania; Department of Physical Therapy, School of Health and Rehabilitation Sciences, University of Pittsburgh, Pittsburgh; Department of Human Genetics, Graduate School of Public Health, University of Pittsburgh, Pittsburgh, Pennsylvania; Section on Geriatrics, Wake Forest University School of Medicine, Winston-Salem, North Carolina; Department of Preventive Medicine, Health Science Center, University of Tennessee, Memphis, Tennessee; Laboratory of Epidemiology, Biometry, and Demography, National Institute on Aging, National Institutes of Health, Bethesda, Maryland; Department of Epidemiology and Biostatistics, University of California, San Francisco, California.

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Katsiaras, Andreas, Annette B. Newman, Andrea Kriiska, Jennifer Brach, Shanthi Krishnaswami, Eleanor Feingold, Stephen B. Kritchevsky, Rongling Li, Tamara B. Harris, Ann Schwartz, and Bret H. Goodpaster. Skeletal muscle fatigue, strength, and quality in the elderly: the Health ABC Study. J Appl Physiol 99: 210–216, 2005. First published February 17, 2005; doi:10.1152/japplphysiol.01276.2004.—We examined the muscle fatigue characteristics in older men and women and determined whether these were related to the size, strength, or quality of muscle. A total of 1,512 men and women aged 70–79 yr from the Health, Aging, and Body Composition Study participated in this study. Muscle cross-sectional area and attenuation were determined with computed tomography. Skeletal muscle fatigue and strength (peak torque) of the knee extensors and flexors were measured using isokinetic dynamometry. Men were more fatigue resistant than women for both knee extension (fatigue index: 70.4 ± 13.3 Nm; both P < 0.05) and knee flexion (67.9 ± 16.4 Nm; both P < 0.05). Peak torque and muscle quality (specific torque) were higher in men than women for knee extension (99.6 ± 28.2 Nm vs. 63.0 ± 16.8 Nm; both P < 0.05) and knee flexion (74.0 ± 26.4 Nm vs. 49.6 ± 15.9 Nm; both P < 0.05). Total work and power output was greater in men compared with women for both the quadriceps (1353 ± 451 vs. 832 ± 264 J; both P < 0.05) and the hamstrings (741 ± 244 vs. 510 ± 141 J; both P < 0.05). In both genders, the quadriceps was able to perform more work with greater power compared with the hamstrings. Those who were stronger actually had greater fatigue after adjusting for age, race, physical activity, and total body fat. In conclusion, older men were more fatigue resistant than women, although in both men and women greater fatigue was not related to muscle weakness.

Incidence of hip fractures (6, 7) and incident mobility limitations (10). However, because many activities do not require maximal efforts but rather repeated sustained submaximal efforts, muscle fatigue may be particularly relevant to the age-associated loss of function. Moreover, because both muscle strength and muscle fatigue can vary dramatically within individuals (43, 47), it is not known whether strength and muscle fatigue within older men and women are related. In contrast to muscle strength, relatively little is known about skeletal muscle fatigue in the elderly. Additional studies of muscle fatigue in older adults are needed to complement our understanding of the age-associated loss of muscle function.

Skeletal muscle fatigue can be defined as the decline in the force generation capacity of muscle over a series of repeated contractions or sustained contractions (22).

Fatigue resistance, sometimes referred to as muscle endurance, has been defined as time to failure to maintain a target tension (27). Several studies have reported that women are more fatigue resistant than men (8, 21, 28, 29, 36, 40, 42, 46, 53, 61), although this has not been a consistent observation (5, 9, 18, 30, 32, 46). Moreover, some studies have reported that muscle of young adults is more fatigue resistant than older adults (15, 16, 36). Yet others have reported greater fatigue resistance in older adults (8, 9, 12, 15, 19, 28, 30, 36, 44). These inconsistencies may be due to the rather variable methodologies implemented to quantify fatigue as well as different muscle groups tested (e.g., elbow flexors, knee extensors, adductor pollicis, ankle dorsiflexors), the mode of exercise utilized (e.g., isometric, isokinetic, dynamic, electrically induced fatigue), the particular study populations and the relatively small number of subjects studied.

In this study, we utilized the Health, Aging, and Body Composition (Health ABC) cohort of older relatively well-functioning men and women to describe muscle fatigue characteristics of two distinct muscle groups in parallel with measures of strength and muscle mass. The general study design and overall purpose of this longitudinal observational study...
have been described elsewhere (23, 48, 58–60). The primary purpose of this particular cross-sectional study was to describe knee extensor and flexor fatigue characteristics in older adults. We also sought to determine whether fatigue is different in men and women, whether fatigue varies according to distinct muscle groups, and whether fatigue is related to strength or muscle mass.

METHODS

Study Population

The Health ABC study is a longitudinal study of 3,075 black and white men and women, residing in Pittsburgh, PA and Memphis, TN. The population was recruited from a random sample of Medicare-eligible adults aged 70–79 yr residing in the study areas.

Inclusion criteria have been described in detail elsewhere (23, 48, 58–60) and included the following: ambulation without the use of an assistive device (cane, walker, crutches), no difficulty performing activities of daily living, and no difficulty in walking one-quarter of a mile or climbing 10 steps without resting.

Whole body fat mass and fat-free mass were obtained using fan-beam dual-energy X-ray absorptiometry (DXA; model QDR 4500, Hologic, Waltham, MA). Age, height, and weight were obtained from each participant, after which a body mass index (BMI) was calculated as weight (kg)/height (m²). A questionnaire was used to assess the physical activity patterns of the past 7 days. Each activity-intensity combination was assigned a metabolic equivalent (MET) to calculate the rate of kilocalories per week per activity. A minimum of 28 repetitions was used as an arbitrary number to designate a >90% completion of the task at hand. Fatigability (i.e., fatigue index in %) of the quadriceps and hamstring muscles was calculated as the percent decline from peak torque: (final torque/initial torque) × 100. Higher values indicate a higher level of fatigue resistance of the associated muscle; lower values reflect greater fatigue. To help ensure that maximal contractions were attained throughout the test, the technician provided verbal encouragement throughout the test. Participants were instructed to avoid pacing and were therefore excluded from the primary analysis if their fatigue index was >100% or if they performed fewer than 28 of 30 repetitions during either the knee extension or knee flexion. A fatigue index >100% would mean that the force of contraction became greater throughout the test, which would be highly unlikely and can be viewed as pacing. Initial peak torque, total work, and power were also obtained from the fatigue test. Muscle-specific torque, that is, peak torque per cross-sectional area, was calculated as an index of muscle quality.

CT

Skeletal muscle composition (23, 48, 58–60) was assessed via CT 2 yr earlier (in Pittsburgh, PA: 9800 Advantage, General Electric, Milwaukie, WI; in Memphis, TN: Somatom Plus 4, Siemens, Erlangen, Germany, and PQ 2000S, Marconi Medical Systems, Cleveland, OH). To localize the midthigh position, an anterior-posterior scout scan of the entire femur was obtained. The femoral length was measured in cranial-caudal dimension, and the scan position was determined as the midpoint of the distance between the medial edge of the greater trochanter and the intercondylloid fossa of the right leg. A single 10-mm slice (120 kVp and 200–250 mA) was obtained at the femoral midpoint. On acquisition, all images were transferred electronically to a central reading center and analyzed by a single observer using a SUN workstation (SPARC station II, Sun Microsystems, Mountain View, CA). Proprietary software using the IDL development platform (RSI Systems, Boulder, CO) was utilized to calculate skeletal muscle and adipose tissue areas of the thigh. Tissue areas were calculated by multiplying the number of pixels of a given tissue type by the pixel area. The mean attenuation coefficient values of muscle within the regions outlined on the images were determined by averaging the CT number (pixel intensity) in Hounsfield units (HU), where 0 equals the HU of water and ~100 equals the HU of air (24). Adipose and skeletal muscle tissue areas for each participant were distinguished by a bimodal image histogram resulting from the distribution of CT numbers in adipose tissue and skeletal muscle tissue (52). Subcutaneous adipose tissue (STAT) area was distinguished from intermuscular adipose tissue (IMAT) area by manually drawing a line along the deep fascial plane surrounding the thigh muscles. Once the adipose tissue was segmented from the images, the individual muscles were identified again utilizing manual tracing. The total area of nonadipose, nonbone tissue within the deep fascial plane was used as a measure of muscle area.

Statistical Analysis

Descriptive statistics, including means, medians, standard deviations, and ranges were computed. The distribution of the muscle characteristics was examined, and nonparametric tests of the median were used for the univariate analyses. Muscle fatigue, strength, mass, and composition were compared in men and women using the Wilcoxon rank sum test because the distributions were skewed. Gender-specific associations between skeletal muscle fatigue (peak torque, total work, fatigue index) and muscle composition (muscle area, muscle attenuation, intermuscular fat) were evaluated using Spearman correlation. To assess the independent association of specific torque on muscle fatigue by gender (during extension and flexion) controlling for age, race, physical activity, body fat, and muscle density, multiple regression analysis was performed. The statistical significance of the various tests was assessed using a two-sided hypothesis test using the SAS system (version 8.2 for Windows, SAS Institute, Cary, NC). For the present study, only individuals with complete CT and DXA data as well as valid fatigue tests were included in the analysis.

RESULTS

Subject Characteristics

Characteristics of men and women who had valid fatigue tests are depicted in Table 1. The cohort was approximately...
evenly distributed between men and women, with 37% of the population being black. Men were taller, were heavier, and had a greater amount of fat-free mass than women, and women had more body fat than men. Black women had a significantly greater BMI, body weight, body fat, and fat-free mass than white women. White men had a greater proportion of body fat and less fat free mass than black men. Ten percent of subjects completed the fatigue test using their left leg, and accordingly, CT data for their left leg were analyzed. CT and muscle fatigue test results for left and right legs were pooled. None of the anthropometric or body composition parameters was different for men who were excluded on the basis of an invalid fatigue test. However, women who were excluded on the basis of having an invalid fatigue test had less fat free mass.

**Skeletal Muscle Composition**

Skeletal muscle composition characteristics of those with valid fatigue tests are depicted in Table 2 and are similar to that reported previously for the entire cohort (23).

All groups had a greater quadriceps cross-sectional area and density compared with hamstrings. Men had greater quadriceps and hamstrings muscle cross-sectional area and less (P < 0.05) STAT area than women. Men and women had similar amounts of IMAT area. Men had significantly higher muscle density, reflecting lower muscle lipid content. Black men had more muscle, greater muscle density, and more IMAT than white men. Similarly, black women had greater muscle area, lower muscle density, and more IMAT and STAT than white women.

**Skeletal Muscle Fatigue Characteristics**

**Gender differences in fatigue.** Gender differences in skeletal muscle fatigue are depicted in Table 3 for knee extension and knee flexion, with Table 4 exhibiting the specific P values for all fatigue index comparisons. Men were more fatigue resistant than women as evidenced by their higher values for fatigue index during both knee extension and knee flexion. Men were stronger (higher peak torque), had greater muscle quality (specific torque), and produced more total work and power compared with women during both knee extension and knee flexion. Men and women who were excluded from these analyses on the basis of fatigue indexes >100% had significantly lower (P < 0.05) peak torque, specific torque, total work, repetitions, and power during both knee extension and knee flexion. This suggests that these subjects did not produce a maximal voluntary effort during the fatigue test, supporting our rationale to exclude them from the primary analysis.

**Racial differences in fatigue.** There were no significant racial differences in muscle fatigue for men (Tables 3 and 4). In women, there were no significant differences for knee extensors, although the knee flexors of white women were more fatigue resistant compared with black women (Tables 3 and 4). Muscle quality and power were slightly but significantly higher in white men for both muscle groups. Black women were able to perform a significantly greater amount of total work (knee extension) and had significantly (P < 0.05) greater peak torque values (knee extension and flexion), whereas white women exhibited a better muscle quality as indicated by the higher muscle-specific torque (knee extension and flexion). No differences were observed in power between the two groups of women.

**Knee extension vs. knee flexion.** Peak torque, total work, and power were all significantly lower during knee flexion compared with knee extension in both men and women. Men, but not women, exhibited lower fatigue index values during knee flexion. However, the specific torque (peak torque per cross-sectional area) of knee flexors was 52% higher in men and 47%

### Table 1. Characteristics of men and women

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>White Men</th>
<th>Black Men</th>
<th>White Women</th>
<th>Black Women</th>
<th>All Men</th>
<th>All Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>475</td>
<td>238</td>
<td>482</td>
<td>317</td>
<td>713</td>
<td>799</td>
</tr>
<tr>
<td>Age, yr</td>
<td>75.8 ± 2.9*</td>
<td>75.3 ± 2.7</td>
<td>75.4 ± 2.7</td>
<td>75.3 ± 2.8</td>
<td>75.6 ± 2.8†</td>
<td>75.3 ± 2.8</td>
</tr>
<tr>
<td>Height, m</td>
<td>1.7 ± 0.06</td>
<td>1.73 ± 0.07</td>
<td>1.59 ± 0.06</td>
<td>1.60 ± 0.06†</td>
<td>1.73 ± 0.06†</td>
<td>1.59 ± 0.06†</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>80.9 ± 12.2</td>
<td>81.1 ± 13.5</td>
<td>65.2 ± 11.5</td>
<td>74.1 ± 14.4*</td>
<td>81.0 ± 12.6†</td>
<td>68.7 ± 13.5</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>26.9 ± 3.6</td>
<td>27.0 ± 3.9</td>
<td>25.6 ± 4.1</td>
<td>29.1 ± 5.5*</td>
<td>26.9 ± 3.7</td>
<td>27.0 ± 5.0</td>
</tr>
<tr>
<td>Body fat, kg</td>
<td>24.0 ± 7.0*</td>
<td>22.5 ± 7.4</td>
<td>25.8 ± 7.5</td>
<td>29.7 ± 9.4*</td>
<td>23.5 ± 7.2</td>
<td>27.3 ± 8.5†</td>
</tr>
<tr>
<td>Fat-free mass, kg</td>
<td>56.7 ± 6.7</td>
<td>58.2 ± 7.7*</td>
<td>39.2 ± 5.0</td>
<td>43.6 ± 6.2*</td>
<td>57.2 ± 7.1†</td>
<td>40.9 ± 5.9</td>
</tr>
<tr>
<td>Body fat, %</td>
<td>29.2 ± 4.9*</td>
<td>27.2 ± 5.4</td>
<td>39.0 ± 5.6</td>
<td>39.6 ± 5.9</td>
<td>28.6 ± 5.2</td>
<td>39.2 ± 5.7†</td>
</tr>
</tbody>
</table>

Values are means ± SD. *Significantly greater racial differences within genders, P < 0.05 (via Wilcoxon rank sum test). †Significantly greater gender difference, P < 0.05 (via Wilcoxon rank sum test).

### Table 2. Skeletal muscle composition characteristics of men and women

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>White Men</th>
<th>Black Men</th>
<th>White Women</th>
<th>Black Women</th>
<th>All Men</th>
<th>All Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh total area, cm²</td>
<td>196.2 ± 34.3</td>
<td>212.0 ± 40.1*</td>
<td>197.9 ± 45.6</td>
<td>241.6 ± 59.9*</td>
<td>201.5 ± 37.1</td>
<td>215.2 ± 56.0†</td>
</tr>
<tr>
<td>Quadriceps area, cm²</td>
<td>60.7 ± 9.2</td>
<td>64.9 ± 10.6*</td>
<td>39.8 ± 6.4</td>
<td>46.2 ± 8.7*</td>
<td>62.1 ± 9.9†</td>
<td>42.3 ± 8.0</td>
</tr>
<tr>
<td>Hamstrings area, cm²</td>
<td>30.0 ± 5.8</td>
<td>33.7 ± 6.4*</td>
<td>21.1 ± 3.5</td>
<td>25.6 ± 4.5*</td>
<td>31.3 ± 6.2†</td>
<td>22.9 ± 4.5</td>
</tr>
<tr>
<td>Intermuscular adipose tissue area, cm²</td>
<td>9.1 ± 6.2</td>
<td>10.7 ± 6.4*</td>
<td>8.3 ± 4.2</td>
<td>12.1 ± 6.9*</td>
<td>9.6 ± 6.3</td>
<td>9.8 ± 5.7</td>
</tr>
<tr>
<td>Subcutaneous adipose tissue area, cm²</td>
<td>46.5 ± 19.7</td>
<td>48.4 ± 20.0</td>
<td>95.8 ± 36.5</td>
<td>117.0 ± 46.4*</td>
<td>47.1 ± 19.8</td>
<td>104.2 ± 42.0†</td>
</tr>
<tr>
<td>Thigh density, HU</td>
<td>37.6 ± 6.5</td>
<td>37.7 ± 6.2</td>
<td>35.5 ± 6.3*</td>
<td>33.5 ± 6.2</td>
<td>37.6 ± 6.4†</td>
<td>34.7 ± 6.4</td>
</tr>
<tr>
<td>Quadriceps density, HU</td>
<td>43.6 ± 5.8</td>
<td>43.8 ± 5.8</td>
<td>40.5 ± 6.0*</td>
<td>38.4 ± 6.1</td>
<td>43.7 ± 5.8†</td>
<td>39.7 ± 6.1</td>
</tr>
<tr>
<td>Hamstrings density, HU</td>
<td>30.1 ± 8.6</td>
<td>32.1 ± 8.0*</td>
<td>28.5 ± 7.9</td>
<td>27.6 ± 8.1</td>
<td>30.8 ± 8.4†</td>
<td>28.1 ± 8.0</td>
</tr>
</tbody>
</table>

Values are means ± SD; n, no. of subjects. HU, Hounsfield units. *Significantly greater racial differences within gender P < 0.05 (via Wilcoxon rank sum test). †Significantly greater gender differences, P < 0.05, via Wilcoxon rank sum test.

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higher in women (both $P < 0.05$) compared with knee extensors.

**Association of Fatigue With Skeletal Muscle Composition, Strength, and Quality**

Muscle fatigue in both men and women was inversely associated ($P < 0.05$) with peak torque as well as muscle-specific torque during knee extension ($\rho = -0.305$ and $\rho = -0.341$ in men; $\rho = -0.263$ and $\rho = -0.326$ in women) and during knee flexion ($\rho = -0.338$ and $\rho = -0.326$ in men; $\rho = -0.407$ and $\rho = -0.362$ in women). Fatigue of knee extensors or flexors was not associated with size or density of these muscles in either men or women. Multivariate regression analyses in men and women revealed that muscle-specific torque was independently and negatively associated with skeletal muscle fatigue after adjusting for age, race, physical activity, total body fat, and muscle density during knee extension (Table 5) and knee flexion (Table 6). The model accounted for 11% of the variance in knee extension fatigue for both genders, whereas 11 and 21% of the total variance in knee flexion could be accounted for in men and women, respectively.

Muscle strength (peak torque) was positively related ($P < 0.05$) to muscle cross-sectional area in both men ($\rho = 0.399$, $\rho = 0.232$) and women ($\rho = 0.381$, $\rho = 0.188$) during extension and flexion, respectively. Having more IMAT was positively ($P < 0.05$) associated with peak torque during knee extension in both genders (men: $\rho = 0.082$; women: $\rho = 0.147$). A similar association between IMAT and knee flexion was only found in women ($\rho = 0.116$; $P < 0.05$). In both genders, STAT exhibited somewhat stronger positive associations with peak torque during knee extension ($\rho = 0.123$ in men; $\rho = 0.186$ in women; both $P < 0.05$) than during knee flexion ($\rho = 0.081$ in men; $\rho = 0.116$ in women; both $P < 0.05$).

**DISCUSSION**

Most studies of muscle function of older adults have focused on strength, thereby overlooking muscle fatigue as a potentially important link to normal activities of daily living requiring submaximal sustained activity rather than maximal efforts. This is the first large-scale description of skeletal muscle fatigue measured in conjunction with measures of muscle strength in older adults. The present study lends unique insight into the potential importance of muscle fatigue in older adults, including gender, racial, and muscle group differences. In addition, this study underscores the potential caveats, technical and logistical considerations in the measure of muscle fatigue in an older population.

Men in this older cohort, in addition to being stronger and having a greater specific torque and work capacity, were more fatigue resistant than women, an observation that was consistent for both quadriceps and hamstrings muscle groups. This is in contrast with other studies reporting that women are more fatigue resistant than men (8, 21, 28, 29, 40, 42, 46, 53, 61). However, greater fatigue resistance in women has not been a universal observation (5, 9, 19, 30, 32, 46), and indeed, one

### Table 3. Skeletal muscle fatigue characteristics during knee extension and knee flexion

<table>
<thead>
<tr>
<th></th>
<th>White Men (n = 475)</th>
<th>Black Men (n = 238)</th>
<th>White Women (n = 482)</th>
<th>Black Women (n = 317)</th>
<th>All Men (n = 713)</th>
<th>All Women (n = 799)</th>
<th>Excluded Men (n = 273)</th>
<th>Excluded Women (n = 186)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Knee extension</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue index, %</td>
<td>70.1 ± 14.5</td>
<td>71.2 ± 16.8</td>
<td>67.0 ± 14.2</td>
<td>66.7 ± 14.5</td>
<td>70.4 ± 15.3</td>
<td>66.9 ± 14.3</td>
<td>103.4 ± 24.8</td>
<td>99.8 ± 38.1</td>
</tr>
<tr>
<td>Peak torque, Nm</td>
<td>98.9 ± 25.3</td>
<td>101.2 ± 33.3</td>
<td>60.6 ± 16.0</td>
<td>66.8 ± 17.3</td>
<td>99.6 ± 28.2</td>
<td>63.0 ± 16.8</td>
<td>83.4 ± 25.1</td>
<td>54.3 ± 18.9</td>
</tr>
<tr>
<td>Specific torque, Nm/cm²</td>
<td>1.64 ± 0.40</td>
<td>1.57 ± 0.47</td>
<td>1.54 ± 0.39</td>
<td>1.47 ± 0.39</td>
<td>1.62 ± 0.43</td>
<td>1.51 ± 0.39</td>
<td>1.33 ± 0.37</td>
<td>1.23 ± 0.37</td>
</tr>
<tr>
<td>Total work, J</td>
<td>1,369 ± 425</td>
<td>1,320 ± 498</td>
<td>813 ± 256</td>
<td>860 ± 274</td>
<td>1,353 ± 451</td>
<td>832 ± 264</td>
<td>1,121 ± 454</td>
<td>690 ± 296</td>
</tr>
<tr>
<td>Repetitions, no.</td>
<td>30.0 ± 0.08</td>
<td>30.0 ± 0.06</td>
<td>29.9 ± 0.08</td>
<td>30.0 ± 0.06</td>
<td>30.0 ± 0.07</td>
<td>29.9 ± 0.07</td>
<td>29.2 ± 3.5</td>
<td>28.2 ± 4.7</td>
</tr>
<tr>
<td>Power, W</td>
<td>89.7 ± 31.5</td>
<td>83.8 ± 37.1</td>
<td>52.8 ± 18.3</td>
<td>54.1 ± 20.8</td>
<td>87.7 ± 33.5</td>
<td>53.3 ± 19.2</td>
<td>74.7 ± 33.3</td>
<td>43.6 ± 20.6</td>
</tr>
<tr>
<td><strong>Knee flexion</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue index, %</td>
<td>68.4 ± 16.5</td>
<td>67.0 ± 16.2</td>
<td>67.0 ± 16.8</td>
<td>61.7 ± 18.3</td>
<td>67.9 ± 16.4</td>
<td>64.9 ± 17.6</td>
<td>104.2 ± 27.8</td>
<td>100.2 ± 30.8</td>
</tr>
<tr>
<td>Peak torque, Nm</td>
<td>73.9 ± 24.6</td>
<td>74.1 ± 29.8</td>
<td>48.1 ± 15.5</td>
<td>51.9 ± 16.3</td>
<td>74.0 ± 26.4</td>
<td>49.6 ± 15.9</td>
<td>66.0 ± 20.9</td>
<td>44.2 ± 16.9</td>
</tr>
<tr>
<td>Specific torque, Nm/cm²</td>
<td>2.57 ± 1.42</td>
<td>2.26 ± 0.95</td>
<td>2.31 ± 0.77</td>
<td>2.08 ± 0.78</td>
<td>2.47 ± 1.29</td>
<td>2.22 ± 0.78</td>
<td>2.15 ± 0.74</td>
<td>1.92 ± 0.79</td>
</tr>
<tr>
<td>Total work, J</td>
<td>756 ± 239</td>
<td>710 ± 251</td>
<td>511 ± 133</td>
<td>510 ± 153</td>
<td>741 ± 244</td>
<td>510 ± 141</td>
<td>665 ± 242</td>
<td>427 ± 165</td>
</tr>
<tr>
<td>Repetitions, no.</td>
<td>30.0 ± 0.1</td>
<td>29.9 ± 0.1</td>
<td>29.9 ± 0.1</td>
<td>29.9 ± 0.1</td>
<td>29.9 ± 0.1</td>
<td>29.9 ± 0.1</td>
<td>29.2 ± 3.2</td>
<td>28.2 ± 4.8</td>
</tr>
<tr>
<td>Power, W</td>
<td>37.3 ± 15.4</td>
<td>31.7 ± 16.4</td>
<td>24.0 ± 9.7</td>
<td>23.3 ± 10.9</td>
<td>35.4 ± 16.0</td>
<td>23.7 ± 10.2</td>
<td>32.6 ± 15.7</td>
<td>20.3 ± 9.9</td>
</tr>
</tbody>
</table>

Values are means ± SD; n, no. of subjects. *Significantly greater racial differences within gender, $P < 0.05$. †Significantly greater gender differences, $P < 0.05$. ‡Significantly greater within group between movement (extension vs. flexion) differences, $P < 0.05$. Excluded men and women, fatigue index >100% during either knee extension or knee flexion and/or number of repetitions <28. All comparisons were analyzed via the Wilcoxon rank sum test.
other study also observed greater muscle fatigue in older women than in men (19). There are several possible reasons for these apparently discrepant results. First, muscle fatigue is highly variable among subjects, such that the wide range of physical function in these older but healthy adults could have contributed to a greater variability of measurable fatigue in our study. Most of these prior studies observed gender differences in much younger subjects (21, 29, 42, 46, 53, 61), whereas fewer compared muscle fatigability in older men and women (8, 28, 36, 40). Moreover, the protocols used to assess muscle fatigue have not been consistent. Some studies utilizing isokinetic contractions, similar to that used in the present study, have not observed gender differences in muscle fatigue (6, 32). Examining a relatively large number of subjects likely provided us with more power to detect smaller gender differences in muscle fatigue. However, the relatively large proportion of the subjects excluded from the analysis in our study on the basis of invalid tests, in addition to inconsistencies in the protocols used to measure fatigue, the age and gender composition of the test subjects, and range of function, certainly makes the interpretation of these data more difficult. Lower absolute muscle force production by women has been previously postulated to explain their greater fatigue resistance. It has been suggested that this is related to their lower glycolytic or anaerobic capacity, and a higher oxidative capacity, translating into fatigue resistance (56). Similarly, it has been postulated that a greater proportion and number of type II muscle fibers in men may account for their greater fatigability (46). Gender differences in the pattern of neuromuscular activation (25), hormonal-dependent alterations in muscle temperature (51), muscle blood flow differences arising from changes in mechanical compression (42), and muscle size-dependent substrate utilization (17) have also been suggested as potential mechanisms for the enhanced fatigue resistance in women. Therefore, on one hand, our results do not support previous speculation concerning mechanisms for gender differences in fatigue. Nevertheless, we did find that weaker men and women are indeed more fatigue resistant. Thus these mechanisms that potentially link weakness with muscle fatigue resistance may yet be accurate. Whether they explain potential gender differences in muscle function, however, warrants further investigation.

Muscles involved in knee extension, i.e., quadriceps, and knee flexion, i.e., hamstrings, exhibited some interesting differences that deserve comment. Quadriceps were slightly more fatigue resistant than hamstrings in black men and women but not in white men or women. The greater strength, work, and associated power of quadriceps was consistent across gender and race. However, the lower specific torque in the quadriceps might suggest that the size and strength of these muscles are disassociated. It is possible that the hamstrings, although much smaller, are able to produce more force than quadriceps for a given size; that is, the quality of these muscles differs. Caution should be given to this interpretation because we could not verify whether the respective muscle groups measured on CT were exactly the same muscles actually producing the movement during knee extension and flexion. Previous studies have shown via electromyography that dynamic knee extension activated the quadriceps and tibialis anterior muscles but not the gastrocnemius or hamstrings muscles (4, 20, 57). Moreover, our CT measures were obtained in these subjects 2 yr before the measures of muscle fatigue. Thus there may not be a perfect match between the quantification of muscle size and the functional properties of the respective muscles.

Although muscle weakness is clearly associated with lower muscle mass in aging, muscle quality may be an important parameter of muscle function (23) of older adults. Men had greater quadriceps and hamstrings muscle quality than women.

Table 5. **Linear regression analysis of skeletal muscle fatigue during knee extension**

<table>
<thead>
<tr>
<th></th>
<th>Men</th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>β</td>
<td>SE</td>
</tr>
<tr>
<td>Specific torque</td>
<td>−12.37</td>
<td>1.29</td>
</tr>
<tr>
<td>Body fat</td>
<td>0.0001</td>
<td>0.00009</td>
</tr>
<tr>
<td>Physical activity</td>
<td>0.003</td>
<td>0.007</td>
</tr>
<tr>
<td>Quadriceps density</td>
<td>0.125</td>
<td>0.110</td>
</tr>
<tr>
<td>Age</td>
<td>0.049</td>
<td>0.195</td>
</tr>
<tr>
<td>Race</td>
<td>0.345</td>
<td>1.167</td>
</tr>
</tbody>
</table>

Partial R² is the explained variance of each specific parameter in the model. Total variance (R²) by the models was 0.11 for men and 0.11 for women. Specific torque was calculated as the peak torque during knee extension divided by quadriceps muscle area.
This is consistent with the findings of Lynch et al. (41) from the Baltimore Longitudinal Study of Aging in which men had higher muscle quality in both arms and legs. Although we did not intend to examine the association between age and muscle function in this cross-sectional analysis of a relatively narrow age range of older adults, age-associated decreases in muscle quality have been shown in both men and women in cross-sectional (3, 39, 41) but not longitudinal studies (45). We did not observe an association between age and muscle fatigue. Aging has been reported to possess a greater level of fatigue resistance (8, 9, 12, 19, 28, 30, 44), but this has not been a consistent observation (5, 15, 16, 26, 32, 33, 36, 40, 55).

Many factors may account for age- and gender-associated differences in muscle quality and fatigue, including changes within specific muscle fiber types (34), pennation angle of the muscle (1), patterns of motor recruitment (2), and greater amount of connective tissue within the muscle in the elderly (50). Skeletal muscle undergoes architectural and morphological changes with age, including decreasing proportion of type II fibers (35). Although the cause of the age-associated skeletal muscle atrophy is debated (38, 49), a decrease in the size of type II fibers is a common observation (13, 35, 37), which may be related to the loss of the type II motor units (11). Another morphological adaptation with aging that may relate to fatigue is an increase of hybrid fiber types containing the faster contracting myosin heavy chain IIa protein (14, 31, 34, 62). We can only speculate that quantitative and qualitative changes within the lower extremity musculature of older adults may explain some of the gender and muscle group differences in muscle fatigue and quality. These morphological changes may also account for significantly greater muscle work capacity and power in white compared with black men, possibly translating into a greater ability for explosive muscle performance, which may be clinically relevant for the prevention of falls (54). Moreover, although differences in physical activity levels may also explain the potential gender, racial, and muscle group differences in skeletal muscle fatigue, there were no gender differences in physical activity. It is not clear whether the higher reported physical activity levels in white than black women was related to their differences in muscle quality.

Despite the novel findings, the present investigation has several limitations. Many of these older subjects were excluded from the primary analysis because their force production did not decline during the repeated muscular contractions, implying that they did not produce a voluntary maximal effort. Although the verbal encouragement provided was identical for all participants, it is possible that psychosocial or motivational factors were associated with muscle fatigue. Another limitation was that these measures of muscle strength and fatigue were made within a relatively healthy older population. It is possible that stronger associations may have been observed had older adults with less functional capacity been studied.

In summary, we have extensively described skeletal muscle fatigue in a population of well-functioning elders in conjunction with measures of strength and muscle quality. These data suggest that muscle fatigue is a distinct parameter of muscle function that is not associated with either low muscle mass or muscle weakness in older men and women. Future follow-up studies within this cohort may be able to determine whether muscle fatigue, in addition to the strength and quality of quadriceps and hamstrings, contributes to the loss of function or incident mobility limitations. Daily activities likely rely differently on quadriceps and hamstrings, which could imply that specific muscle groups could be differentially affected by interventions designed to improve function or reduce the risk for disability. The present study lays the groundwork for further examination of muscle fatigue as a potentially important factor in the age-associated decline in function.

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