Effect of old age on human skeletal muscle force-velocity and fatigue properties

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Callahan DM, Kent-Braun JA. Effect of old age on human skeletal muscle force-velocity and fatigue properties. J Appl Physiol 111: 1345–1352, 2011. First published August 25, 2011; doi:10.1152/japplphysiol.00367.2011.—It is generally accepted that the muscles of aged individuals contract with less force, have slower relaxation rates, and demonstrate a downward shift in their force-velocity relationship. The factors mediating age-related differences in skeletal muscle fatigue are less clear. The present study was designed to test the hypothesis that age-related shifts in the force-velocity relationship impact the fatigue response in a velocity-dependent manner. Three fatigue protocols, consisting of intermittent, maximum voluntary knee extension contractions performed for 4 min, were performed by 11 young (23.5 ± 0.9 yr, mean ± SE) and 10 older (68.9 ± 4.3) women. The older group fatigued less during isometric contractions than the young group (to 71.1 ± 3.7% initial torque and 59.8 ± 2.5%, respectively; P = 0.02), while the opposite was true during contractions performed at a relatively high angular velocity of 270°·s⁻¹ (old: 28.0 ± 3.9% initial power, young: 52.1 ± 6.9%; P < 0.01). Fatigue was not different (P = 0.74) between groups during contractions at an intermediate velocity, which was selected for each participant based on their force-velocity relationship. There was a significant association between force-velocity properties and fatigue induced by the intermediate-velocity fatigue protocol in the older (r = 0.72; P = 0.02) and young (r = 0.63; P = 0.04) groups. These results indicate that contractile velocity has a profound impact on age-related skeletal muscle fatigue resistance and suggest that changes in the force-velocity relationship partially mediate this effect.

force-velocity relationship; knee extensor muscles; specific strength; power

Despite numerous investigations, the relationship between old age and fatigue resistance (the ability to maintain force output during contractions) remains unclear. While some studies report that older adults resist muscle fatigue more than young (9, 11, 18, 28, 42, 46), other studies find the opposite to be true (2, 4, 44), and yet others find no difference in fatigue resistance across age groups (1, 5, 20, 33, 38, 41, 50). Differences in study design have been suggested to explain some of this variability, and a review of the literature produces an interesting trend: an age-related increase in fatigue resistance is most commonly observed in studies that use isometric contractions to induce fatigue. In contrast, when dynamic contractions are performed, it is more common to observe no difference in fatigue between groups (20, 33, 38, 41), or greater fatigue in the older group (2, 4, 16, 44). Indeed, a recent systematic review indicated that contraction mode is a significant modifier of fatigue resistance in the aged (10).

In studies of the adductor pollicus muscle in young adults, fatigue induced a down- and leftward shift in the force-velocity relationship (26), similar to that observed in the nonfatigued muscles of older adults compared with younger adults (24, 31, 45, 52). Thus it is plausible that the compounding effects of age and fatigue result in particular difficulties for older individuals attempting to maintain force output at rapid contraction velocities. That is, as the force-velocity curve is depressed with repeated contractions, the decline in torque production at high contraction velocities would be relatively greater in older adults.

Age-related reductions in specific strength [force per unit muscle cross-sectional area (CSA)] and neural activation have been suggested to account for differences in fatigue resistance between young and older individuals (50). However, most studies indicate that these factors do not play a significant role in age-related differences in skeletal muscle fatigue during isometric contractions (4, 11, 28, 39). Until recently (12), the extent to which muscle size relates to force production across a range of velocities has been relatively unexplored in the context of old age and accurate quantitation of neural activation during dynamic contractions has proven difficult.

While some investigators have examined the relationship between age and fatigue resistance across multiple contraction modes (4, 7, 35), we are not aware of any studies that have compared the fatigue response at multiple concentric angular velocities. Nor have these results been placed in the context of age-related changes in the force-velocity relationship. The overall goal of the present study was to identify differences in the force-velocity relationship between young and older women and to determine their influence on the ability to produce and maintain force during repeated voluntary contractions.
The protocols used in this study were designed to test four related hypotheses: 1) the unfatigued knee extensor muscles of older women would show a downward shift in the force-velocity relationship compared with young women; 2) older women would fatigue relatively less than young women during 4 min of intermittent maximal voluntary isometric contractions (MVIC); 3) older women would fatigue more than young women during maximal voluntary dynamic contractions (MVDC) at a high velocity (MVDC\textsubscript{h}); and 4) fatigue would be similar between young and old women during MVDC at an intermediate velocity (MVDC\textsubscript{int}) selected to account for interindividual differences in the force-velocity relationship.

**METHODS**

**Participants.** Eleven young (21–30 yr) and 10 older (65–76 yr) community-dwelling women were studied. Physician’s consent was obtained before enrollment of all older participants. Written, informed consent, approved by the University of Massachusetts, Amherst Institutional Review Board, was signed by each participant before enrollment. All study procedures were in accordance with the guidelines established by the Declaration of Helsinki.

The study was restricted to women to avoid potential sex-by-age interactions, and because women are at greater risk for developing future mobility impairments than men (25). Participants were relatively sedentary, reporting less than three 20-min sessions of structured exercise per week. They were also healthy by self-report, as evaluated by health-history questionnaire, and did not take medications known to affect neuromuscular, metabolic, or cardiovascular function. All participants answered “no” to all questions on the Physical Activity Readiness Questionnaire (53).

**Study design.** The study protocol consisted of four visits to the Muscle Physiology Laboratory. On day 1, physical function was measured, as was knee extensor strength and power. Voluntary activation of the knee extensor muscles was assessed using myoelectric stimulation. Days 2–4 were designated for fatigue testing. The isometric protocol and two dynamic fatigue protocols were performed in random order across these 3 days.

**Physical function and activity.** Physical function was assessed by timed tests of stair ascent, descent, and repeated chair stands. Stair ascent and descent times were measured on a flight of eight steps, and the faster of two attempts was recorded for each test. The time to complete 10 chair stands was measured using a standard, square-backed chair (height = 46.0 cm). Participants were instructed to fully stand and sit 10 times as fast as possible, without using their arms. Participants then wore a uniaxial accelerometer to monitor physical activity for 7 days (Actigraph, Pensacola, FL). The average accelerations (60-s epoch) for 5 days, including at least 1 weekend day, were taken to represent total physical activity.

**Muscle isometric strength and power.** Because torque was the measure used to assess knee extensor muscle function in this study, fatigue and contractile characteristics are reported in Newton meters. However, when referring to the effect of contractile velocity on the ability of muscle to generate force, the term “force-velocity” will be used. Although torque-angular velocity may be more appropriate to these findings, force-velocity refers more generally to the inherent behavior of skeletal muscle.

A BiodeX System 3 dynamometer (BiodeX Medical Systems, Shirley, NY) was used to test knee extensor isometric torque and power. Participants were seated with the hips flexed at 90° and the knee flexed at 100° (180° = full extension). Participants sat with their hands across the chest and, after familiarization with the movement, were instructed to “kick as hard as you can” for 3–4 s, while measures of MVIC torque were obtained. During MVDC, participants were instructed to kick as hard and fast as possible, and to stop when their limb reached the limit of a predefined range of motion (ROM = 70°).

At this point in the ROM, the lever arm on the dynamometer applied a resistive torque that limited further extension. These methods were applied to strength and fatigue measures on all days of testing.

Analog signals corresponding to torque, position, and velocity were acquired from the dynamometer and sampled at 2,500 Hz during electrically stimulated measures, and at 1,000 Hz for all voluntary contractions. Posttesting analysis was performed as reported previously (36). Briefly, peak torque was taken from the period during which velocity was stable and equal to target for the given contraction. Power was calculated as the product of peak torque and the corresponding velocity observed at that time.

On the first visit, peak knee extension torque was measured under isometric conditions and at 12 discrete angular velocities (30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 360, and 400°·s\(^{-1}\)) to establish the torque-angular velocity relationship for each subject. The peak torque achieved at each angular velocity was measured and expressed as a percentage of baseline isometric torque. A second-order polynomial was fit to the data, and the equation describing this curve was used to characterize each participant’s force-velocity relationship. This relationship was summarized as the velocity at which 50% of peak isometric torque was generated (\(V_{50}\)) (Fig. 1).

**Myoelectric stimulation.** Motor point electrical stimulation was used to estimate each subject’s ability to fully activate the knee extensor muscles and to quantify muscle contractile characteristics. Two 7.6 × 12.7-cm electrodes were placed transversely across the thigh. One electrode was placed 2–3 cm proximal to the superior border of the patella, and the other was placed 3–4 cm distal to the inguinal crease. Stimulation was delivered (200-μs pulse duration, 80 Hz for 500 ms) with a constant-current stimulator (DST7A; Digitimer, Hertfordshire, UK). The current that elicited a contraction resulting in 50% MVIC then was used for each participant, as described previously (7).

During the first visit, the central activation ratio was measured in all participants, to ensure their ability to fully activate the knee extensor muscles during an isometric contraction (27). To quantify central activation ratio, a stimulation train (80 Hz, 500 ms) was applied during the torque plateau of a MVIC. The peak torque generated
before stimulation was divided by the maximum torque achieved during the imposed stimulus and expressed as a percent. All participants were able to achieve activation $>95\%$ using this measure.

Isometric contractile characteristics of electrically stimulated muscle were quantified as the maximal rate of force development, expressed as percentage of peak torque generated per millisecond (%/ms), and the time for torque to decline to 50% of that achieved at the time of the last stimulus ($T_{1/2}$).

**Fatigue testing.** Following the first visit, each fatigue protocol was performed on a separate day, in random order, and with at least 5 days between testing sessions. Identical procedures for establishing baseline MVIC were used before each protocol. All protocols consisted of 4 min of intermittent maximum voluntary contractions, with fatigue measured from the average force produced during the final $\sim 10$ s of each protocol.

Fatigue during isometric contractions was induced by repeated 5-s MVICs, each separated by 5-s rest, resulting in a 50% duty cycle, and a total of 24 contractions. Contractions were quantified by the torque integrated over the middle 4.5 s of the contraction, noted as the time-tension integral (TTI). The initial and final 0.25 s of the contraction were eliminated from the TTI measure, to minimize the influence of variability in the rates of voluntary force development and relaxation. Fatigue was calculated as follows: \[(\text{average of the final } 2 \text{ TTIs})/\text{(average of the highest baseline TTI and the highest TTI observed during the early portion of the protocol)}\] 100.

Dynamic fatigue testing was performed at 2 distinct angular velocities, through the same 70° ROM. For all participants, the high-velocity protocol (MVDC$_{120}$) consisted of 120 maximal dynamic contractions performed once every 2 s at 270°·s$^{-1}$. Fatigue was quantified as follows: \[(\text{average peak power for the final } 5 \text{ contractions})/\text{(average of the highest baseline power and the highest power observed during the protocol)}\] 100.

The second dynamic fatigue protocol (MVDC$_{134}$) was performed at an intermediate velocity that accounted for differences between subjects in the force-velocity relationship. Each participant performed MVDCs at a specific target velocity corresponding to that which elicited $\sim 75\%$ of their baseline MVIC on the first day of testing. Every subject achieved between 70 and 80% of their MVIC at this contractile velocity on the day of dynamic fatigue testing, indicating the consistency of their performance across days. Because contractile velocity, and thus contraction duration, varied between participants (ROM was the same for all participants), contractions were cued to maintain a 30% duty cycle during the 4 min of intermittent contractions. As with all fatigue protocols, an auditory cue for each contraction was produced using a custom-written MatLab program (MathWorks, Natick, MA). Depending on velocity, participants performed between 34 and 170 contractions. Fatigue was quantified in the MVDC$_{134}$ protocol as follows: \[(\text{average peak power from the final } 10 \text{ s of contractions})/\text{(average of the highest baseline power and the highest power observed during the protocol)}\] 100. Each participant achieved target velocity for all contractions in this fatigue protocol.

### Table 1. Group characteristics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Young</th>
<th>Old</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>11</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Age, yr</td>
<td>23.5 ± 0.9</td>
<td>68.9 ± 1.3</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Height, cm</td>
<td>164 ± 2</td>
<td>160 ± 2</td>
<td>0.15</td>
</tr>
<tr>
<td>Body mass, kg</td>
<td>67.7 ± 6.3</td>
<td>68.8 ± 4.0</td>
<td>0.88</td>
</tr>
<tr>
<td>Physical activity, counts·day$^{-1}$</td>
<td>241 ± 30</td>
<td>207 ± 20</td>
<td>0.35</td>
</tr>
<tr>
<td>Chair stand, s</td>
<td>12.6 ± 0.7</td>
<td>15.8 ± 0.8</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Stair ascent, s</td>
<td>3.1 ± 0.1</td>
<td>3.7 ± 0.3</td>
<td>0.06</td>
</tr>
<tr>
<td>Stair descent, s</td>
<td>2.8 ± 0.1</td>
<td>3.4 ± 0.3</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Values are means ± SE; n, group sizes. The groups had similar height, body mass, and daily physical activity. However, the older group required more time to perform repeated chair rises and descend the stairs and tended to take more time to complete the stair ascent task.

**Muscle anthropometry:** On a separate day, magnetic resonance imaging (MRI) was used to determine the largest fat-free CSA (cm$^2$) of the quadriceps muscle group (vastus lateralis, vastus medialis, rectus femoris, and vastus intermedius) using custom software, as reported previously (29). A 3.0-Tesla Siemens MRI system (Siemens, Munich, Germany) was used to acquire 40 T1-weighted axial images, starting at approximately the femoral neck. The image parameters were as follows: $512 \times 512$ matrix, 6-mm slice thickness, 500-ms repetition time, 13-ms echo time, 90° flip angle, 0-cm slice gap. The MRIs spanned a 24-cm section of the thigh, representing the majority of femoral length for all participants.

For each transverse slice of the MRI set, the quadriceps muscle group was outlined, and pixels within this region of interest were distinguished by signal intensity into muscle, fat, and connective tissue components (29). Total area belonging to each tissue type was determined, and an average of three contiguous slices with the greatest muscle CSA was used to define muscle and fat CSA for each subject. Peak MVIC (Nm) was divided by peak fat-free muscle CSA (cm$^2$) to determine specific strength (N·m·cm$^{-2}$). Fat and connective tissue were expressed as percentage of total CSA (%). Due to scheduling difficulty, MRI data were obtained for only 9 of 11 young women.

**Statistical analyses.** One-way ANOVA (age) was used to detect age-related differences in descriptive measures, physical function, activity, anthropometry, baseline torque (MVIC), V$_{50}$, and fatigue in each protocol. One-way (age group) repeated-measures ANOVA was used to compare the force-velocity relationship across age groups. A significant ($P < 0.05$) interaction between age group and contraction angular velocity would indicate an altered force-velocity relationship between age groups.

Simple linear regression was performed, and correlation coefficients were calculated to explore associations between fatigue and V$_{50}$, as well as between fat-free muscle CSA and baseline torque at 0, 120, and 270°·s$^{-1}$. Means ± SEs and precise $P$ values are reported.

### RESULTS

Group characteristics are reported in Table 1. The young and older groups had similar height, body mass, and levels of habitual physical activity. The older group performed the physical function measures more slowly than the young group.

At baseline, the older group produced $\sim 25\%$ less torque during the MVIC compared with the young group (Table 2). Analysis of the force-velocity relationship revealed significant main effects of contraction velocity ($P < 0.01$) and age group ($P = 0.05$), indicating a decrease in torque with increasing

### Table 2. Anatomical and contractile characteristics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Young</th>
<th>Old</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>9</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>MVIC, N·m</td>
<td>161 ± 7</td>
<td>120 ± 7</td>
<td>0.01</td>
</tr>
<tr>
<td>$T_{1/2}$ force relaxation, ms</td>
<td>122 ± 3</td>
<td>145 ± 8</td>
<td>0.01</td>
</tr>
<tr>
<td>Rate of force development, %/ms</td>
<td>1.41 ± 0.09</td>
<td>1.42 ± 0.14</td>
<td>0.94</td>
</tr>
<tr>
<td>Fat-free muscle CSA, cm$^2$</td>
<td>46.9 ± 1.5</td>
<td>33.8 ± 1.8</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Fat CSA, %total CSA</td>
<td>8.5 ± 1.0</td>
<td>14.0 ± 1.0</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Connective CSA, %total CSA</td>
<td>8.0 ± 0.4</td>
<td>9.2 ± 0.6</td>
<td>0.13</td>
</tr>
<tr>
<td>Specific strength, N·m·cm$^{-2}$</td>
<td>3.3 ± 0.1</td>
<td>3.6 ± 0.1</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Values are mean ± SE; n, group sizes. Maximum voluntary isometric contraction (MVIC), fat-free muscle cross-sectional area (CSA), the proportion of fat CSA, and the $T_{1/2}$ (half-time for torque relaxation following tetanic stimulation) are provided. The older group had lower MVIC, smaller fat-free muscle CSA, and longer $T_{1/2}$, as well as a greater proportion of fat in the anterior compartment. Specific strength, the maximal rate of tetanic force development, and proportion of connective tissue in the anterior compartment were not different between groups.

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velocity in both groups, and lower torque production in the older compared with younger women. As hypothesized, there was an age-by-contraction velocity interaction \((P < 0.01)\), such that a progressively greater decrement in torque was observed in the old as velocity increased (Fig. 1). As a result, \(V_{50}\) was lower in old than young subjects \((P = 0.03)\). Likewise, the average velocity selected for the intermediate fatigue protocol (MVDC\(_{\text{int}}\)) tended to be lower in old \((78.0 \pm 29.0^\circ \cdot \text{s}^{-1})\) than young subjects \((103.6 \pm 36.4^\circ \cdot \text{s}^{-1}; P = 0.09)\).

There were no differences between groups in the maximum rate of torque development during the stimulated tetanic contraction (Table 2). However, the \(T_{1/2}\) of force relaxation following the tetanus was slower in the older group than in the young group (Table 2). There was no main effect of age on the angle at which peak torque was achieved for all velocities <360°·s\(^{-1}\) \((P = 0.74, \text{data not shown})\).

Muscle anatomical characteristics also are provided in Table 2. Although fat-free muscle CSA was significantly lower in older women compared with young, isometric-specific strength did not differ between the groups. The older women had relatively greater intramuscular fat content than the younger women, with no difference in connective tissue area (Table 2).

Fat-free muscle CSA was well-correlated with baseline MVIC in both young \((r = 0.69; P < 0.01)\) and older \((r = 0.89; P < 0.01)\) groups (Fig. 2, top). Correlations between fat-free muscle CSA and baseline dynamic torque (Fig. 2, middle and bottom) were significant at 120°·s\(^{-1}\) \((r = 0.81; P < 0.01)\) and 270°·s\(^{-1}\) \((r = 0.75; P = 0.02)\) in the young, but were less so in the old \((120°·\text{s}^{-1}: r = 0.60, 270°·\text{s}^{-1}: r = 0.57, P = 0.08)\). These results indicate dissociation between fat-free muscle size and dynamic torque production in the older subjects and suggest that other factors become relatively more important to torque production at higher contraction velocities.

During the MVIC fatigue protocol, the older group demonstrated greater fatigue resistance than the young group by maintaining a greater proportion of their initial torque at the end of the protocol \((71.1 \pm 3.7\% \text{ initial vs. } 59.8 \pm 2.5\% ; P = 0.02; \text{Fig. 3A})\). In contrast, fatigue induced during the MVDC\(_{\text{hi}}\) protocol was greater in old \((28.0 \pm 3.9\% \text{ initial})\) than in young subjects \((52.1 \pm 6.9\% , P < 0.01; \text{Fig. 3C})\). During MVDC\(_{\text{int}}\), old and young subjects fatigued to a similar degree \((50.9 \pm 6.0\% \text{ initial and } 53.5 \pm 4.8\% , \text{respectively}; P = 0.74; \text{Fig. 3B})\). These results are summarized in Fig. 4.

In a pooled analysis that included young and older participants, \(V_{50}\) and fatigue during MVDC\(_{\text{int}}\) were negatively correlated \((r = -0.53; P = 0.01)\), such that higher \(V_{50}\) values were associated with greater fatigue. This association was also observed in separate analyses for each age group, as shown in Fig. 5 (young: solid line, \(r = -0.63, P = 0.04\); older: dashed line, \(r = 0.72; P = 0.02\)).

**DISCUSSION**

Age-related fatigue characteristics have been the focus of several recent studies, but unexplained differences in study findings limit our understanding of how age impacts skeletal muscle fatigue. The present study was designed to address gaps in the literature, while controlling for potential effects of physical activity and health on muscle fatigue. Here, we present novel information about the relationship between force-velocity characteristics in unfatigued muscle and fatigue resistance in young and older adults. While multiple contraction modes (isometric and dynamic) have been investigated previously \((4, 7, 16, 35)\), these studies did not evaluate fatigue at multiple velocities, nor explicitly examine associations between the force-velocity relationship and fatigue. We hypothesized that age-related changes in force-velocity characteristics influence fatigue resistance in aging skeletal muscle. Our results support this hypothesis and lend clarity to the literature on this important topic.

In the present study, contraction velocity had a profound impact on age-related differences in fatigue resistance (Fig. 4). Confirmation that these differences were due to contraction...
velocity was provided by the intermediate velocity protocol, which elicited nearly identical levels of fatigue in both the old and young participants by accounting for interindividual differences in the force-velocity relationship. Finally, the association between $V_{50}$ and fatigue (MVDC$_\text{int}$), observed in both groups, suggests that, regardless of age, individuals with inherently slower contractile properties may show greater fatigue resistance when contraction velocity is adjusted for individual torque-velocity characteristics (Fig. 5). This relationship was significant, regardless of whether the analysis was performed for each age group separately, or with all participant data pooled. The fact that significant correlations between $V_{50}$ and fatigue during MVDC$_\text{int}$ were observed in both groups independently demonstrates that the strength of the association does not depend on age-related differences in either measure. No associations were observed between $V_{50}$ and fatigue during the MVIC or MVDC$_\text{hi}$ contraction protocols, suggesting that other factors predominate during isometric contractions, or when contraction velocities are sufficiently high. Overall, these data indicate that slower muscles fatigue to a lesser degree than faster muscles when contracting at similar relative velocities in vivo.

In the unfatigued state, increasing velocity leads to a greater reduction in force-generating capacity in older women compared with young in this study (Fig. 1). While the correlation between fat-free muscle CSA and torque output under isometric conditions is strong and comparable in both groups, this

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**Fig. 3.** Changes in torque or power during fatigue protocols. Changes are shown in response to MVIC (A), MVDC at the intermediate velocity (MVDC$_\text{int}$; B), and MVDC at the high velocity (MVDC$_\text{hi}$; C) for young and older groups. Older subjects fatigued less than the young during MVIC ($P = 0.02$; A), but more during MVDC$_\text{hi}$ ($P < 0.01$; C). There was no difference in fatigue between groups during MVDC$_\text{int}$ ($P = 0.74$; B). Values are expressed relative to baseline values.

**Fig. 4.** Fatigue for each protocol. Fatigue at the end of each of three 4-min contraction protocols for young (solid bars) and older (open bars) groups is shown. Values are means ± SE. Differences in fatigue were observed between age groups during MVIC (*$P = 0.02$) and MVDC$_\text{int}$ (*$P < 0.01$), whereas no differences were found between groups during MVDC$_\text{hi}$ ($P = 0.74$). The young group fatigued to a similar extent in each protocol, whereas older experienced more fatigue in the dynamic contractions, with the greatest fatigue induced during MVDC$_\text{hi}$.

**Fig. 5.** Associations between force-velocity characteristics and fatigue. Fatigue (torque, %initial) during repeated MVDC$_\text{int}$ was plotted against $V_{50}$. Linear regression analysis revealed an association between these variables for both young [solid line ($y = -0.17x + 95.8$), $r = -0.63$; $P = 0.04$] and older [dashed line ($y = -0.37x + 124.2$), $r = -0.72$; $P = 0.02$] groups, suggesting that force-velocity characteristics may explain a significant portion of knee extensor fatigue in humans.

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relationship becomes less similar between groups as velocity increases (Fig. 2). Correlations become moderate during dynamic contractions, and regression coefficients progressively decline for the older group. These data suggest that, although muscle size mediates torque output to a large degree when velocity is not a factor, only the young maintain this relationship as velocity increases. In older adults, other factors, such as slowed shortening velocity of single fibers (31), likely exert a greater influence on contractile force at high speeds than fat-free muscle CSA alone. Changes in contractile velocity could be due to altered fiber-type composition (37) or reduced shortening velocity within fiber types (14, 15, 37), although evidence for preserved shortening velocity within fiber types in older muscle also exists (19, 54). Notably, age-related reductions in shortening velocity are likely sensitive to physical activity level (15), highlighting the relevance of the comparable physical activity levels observed between age groups in the present study. Velocity-dependent decrements in neural activation have also been reported in older adults with impaired physical function (12), but this was unlikely to have occurred in our healthy cohort (12, 30). However, the lack of electrically stimulated contractions to confirm full activation at the conclusion of each fatigue protocol is a limitation in the present study.

Similar to reports in the literature demonstrating the importance of age-related loss of muscle power (4, 36, 44), our data point to the important role of contractile velocity as a distinct and functionally relevant variable in muscle function. It is notable that, despite the ~20% lower V_{50} in older compared with young individuals, no such difference was observed in the peak rate of force development during stimulated contractions (Table 2). In part, these results may suggest a role for lower maximal motor unit discharge rates in the slowing of voluntary contractions in the older group, whereas stimulated contractions would be unaffected. However, multiple factors are likely relevant here. For example, tendon stiffness is associated with the rate of knee extensor torque development in vivo (6) and could obscure any effects that altered single-fiber contractile characteristics might have on whole muscle contraction velocity in older adults.

In general, slower contractile properties might also have an effect on the joint angle (muscle length) at which peak torque was acquired. In our study, the young and older groups had similar rates of torque development during electrically stimulated isometric contractions (Table 2), suggesting that time to peak tension likely did not influence age-related changes in the torque-velocity relationship.

Several mechanisms are likely responsible for the age and velocity-specific fatigue characteristics observed in this study. The fact that age-related deficits in muscle force production tend to increase with increasing velocity has been shown in whole muscle during voluntary contractions (24, 36). Slowed rates of unweighted shortening velocity, as have been observed in vitro (31), and decreased ability to produce force at high velocity are thought to be the result of slowed rates of myosin head detachment during acto-myosin cross-bridge cycling (23, 37). These differences in myosin kinetics theoretically would benefit older muscle under isometric conditions, as slowed detachment rates would allow for a greater number of strongly bound cross bridges at any instant and potentially reduce the metabolic cost of contraction, according to the Penn effect (8). However, this same characteristic would inhibit the ability of muscle to produce force during high-velocity maximal contractions, as observed in this study.

A unique contribution of the present study is the association between unfatigued force-velocity characteristics and fatigue in young and old individuals. The older participants’ apparent inability to produce torque at high angular velocities is exacerbated during repeated contractions and has a strong effect on the overall level of fatigue induced by these protocols. In contrast, young women not only maintained a relatively consistent relationship between muscle size and torque production through a range of angular velocities (Fig. 2), but fatigue to a similar extent in each of the three fatigue protocols (Fig. 4). Clearly, age-related impairments in the force-velocity relationship play a role in the presence or absence of fatigue resistance in these individuals.

During repeated, dynamic contractions, metabolic demand is high, and the accumulation of inorganic phosphate and hydrogen ion occurs in both young and older muscle (32). Accumulation of these metabolites has been shown to decrease contractile force and the rate of acto-myosin cross-bridge cycling in vitro (17). Given the lower myosin head detachment rates observed in unfatigued older muscle (23), any further decrease in detachment rate during fatigue would greatly inhibit their capacity to produce power and force at high velocities. Fatigue-induced depression of the force-velocity curve has been shown in young adults during electrically stimulated contractions (26). It is reasonable to expect that, while the slowed contractile characteristics of older muscle may serve to improve its fatigue resistance during isometric contractions, slower kinetics could result in greater fatigue during high-velocity contractions.

In addition to the impact of age-related changes in the force-velocity relationship, differences in cellular metabolism between young and older muscle may contribute to the observed fatigue differences in the present study. The inherent metabolic properties of old muscles have been suggested to confer energetic advantages compared with young during repeated isometric contractions (21, 28, 34, 51). Previous investigations using in vivo assessment of isometrically contracting muscle show that older individuals rely more on oxidative ATP production to meet energetic demands. This “preference” for oxidative metabolism results in comparatively moderate increases in the concentration of inorganic phosphate and hydrogen ion and less fatigue during submaximal and maximal isometric contractions compared with younger adults (28, 34).

The metabolic response of older muscle during fatiguing dynamic contractions is not known. The relatively greater metabolic cost (ATP/unit force) of dynamic contractions (48), combined with increased metabolic cost of developing vs. maintaining force (47), may limit the ability of oxidative ATP production to keep pace with ATP demand during rapid, repeated dynamic contractions (43). This effect could negate any metabolic advantage observed during isometric contractions in older muscle, as observed during the MVD_{hi} protocol in this study. It is also not known how age-related differences in the force-velocity relationship and cellular metabolism might serve to influence the fatigue response during repeated submaximal contractions. It is possible that the slower muscles of older adults may require relatively greater levels of activation to achieve a given velocity, and thereby be disadvantaged.
compared with young adults during repeated, submaximal dynamic tasks. Future studies measuring the metabolic response of muscles in older individuals during repeated dynamic contractions at a range of intensities may shed light on these hypotheses.

This study is the first to specifically address the potential role of age-related changes in the force-velocity relationship in mediating fatigue characteristics across a range of contraction velocities. While older women had greater fatigue resistance compared with young women during isometric contractions, they showed similar fatigue and greater fatigue during dynamic contractions of intermediate and high velocities, respectively. Furthermore, force-velocity characteristics \( (V_{50}) \) in the unfatigued knee extensor muscles were associated with the fatigue produced by repeated dynamic contractions. Given these results, it appears that age-related differences in the force-velocity relationship of the knee extensor muscles play a key role in the fatigue characteristics of this muscle group. The importance of both contraction velocity and force for power production in fresh and fatigued muscle supports the concept that altered muscle characteristics may be critical to development of mobility impairments in the aging population (13, 40).

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DISCLOSURES

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AUTHOR CONTRIBUTIONS

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