Fatigability Is Increased With Age During Velocity-Dependent Contractions of the Dorsiflexors

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Background. Muscle power is more relevant to the activities of daily living than is isometric strength. However, dynamic contractions have received little attention as they relate to the effect of age on muscle fatigue, particularly in very old persons. Thus, the purpose of this study was to investigate fatigue of the dorsiflexors during a velocity-dependent (isotonic) power task in 12 young (26 years), 12 old (64 years), and 12 very old (84 years) men.

Methods. The fatigue protocol involved 25 maximal (as fast as possible) contractions at a load of 20% maximum isometric strength through a 25° range of motion. Electromyographic signals of the tibialis anterior and soleus muscles were recorded to assess agonist activation and antagonist coactivation, respectively.

Results. Fatigability increased progressively with age as muscle power decreased by 13% in young men, 19% in old men, and 24% in very old men. In contrast, agonist activation and antagonist coactivation were unaffected by age. During the fatigue protocol, agonist activity decreased by 3%, 5%, and 4%, whereas antagonist activity increased by 11%, 13%, and 13% in young, old, and very old men, respectively.

Conclusion. These results demonstrate that older adults are more fatigable than young adults during a velocity-dependent power task. This finding is in contrast to the majority of fatigue data previously reported from less functionally relevant isometric or isokinetic tasks.

The perception of the effect of aging on fatigability has shifted a number of times since research into the topic began, and it is still an evolving concept. Prior to formalizing the notion of the task-dependent nature of fatigue (1,2), studies suggested that no differences existed in the fatigability of muscle from young and old adults (3–5). Conversely, many recent studies that manipulated methodology to make the task as similar as possible for all participants, report that older adults exhibit reduced fatigability as compared to young adults in isometric tasks (6–11), but reduced (11) or enhanced (12) fatigability in isokinetic tasks.

Although the information gathered from isometric and isokinetic fatigue tasks is of value, both of these movement types have limited application outside of a laboratory setting. Isometric (constant joint angle) efforts occur relatively infrequently and only assess muscle strength, whereas isokinetic (constant velocity) movements allow the assessment of muscle power but are unnatural. Activities of daily living are instead more isotonic in nature; that is, the load is constant throughout the range of motion and the velocity of the contraction is variable (see Method section for details on the definition of “isotonic” in this study). Recently, a number of studies have emphasized the greater relative importance of muscle power compared to muscle strength (13–20). The use of velocity-dependent (isotonic) contractions permits the assessment of muscle power using a movement type more relevant to physical performance outside of the laboratory. Indeed, contrary to most isometric and isokinetic findings, it was recently reported that old adults (64 years) demonstrated increased fatigability during an isotonic knee-extension task but equivalent fatigue in an explosive sit-to-stand fatigue test (19).

Improved fatigue resistance with age is believed primarily to be the consequence of age-related motor unit (MU) remodeling; a concept that suggests a progressive loss of MUs with age (21–23), beginning with the death of the motor neurons that innervated fast-twitch (FT) muscle fibers (24,25). Whether FT fibers are lost or are reinnervated by a viable motor neuron responsible for slow-twitch (ST) fibers (and thereby adopt a more fatigue-resistant profile), the end result is that a greater percentage of the remaining muscle fibers possess ST properties. As a consequence, MU remodeling is likely to contribute to the age-related slowing of contractile velocity observed under voluntary isotonic conditions (16,19) and electrically evoked isometric conditions (23,26). Thus, although age-related MU remodeling may lead to improved fatigue resistance during an isotonic or isokinetic task, it may also contribute to a reduction in muscle contractile velocity that could adversely affect fatigability during a velocity-dependent power task.

We selected the dorsiflexor muscle group for our isotonic fatigue task because two recent studies (11,12) report conflicting results regarding the effect of aging on dorsiflexor fatigue, i.e., old adults were less fatigable than young adults during isometric and concentric isokinetic protocols (11), but more fatigable than young adults during concentric and eccentric isokinetic tasks (12). Thus, we can provide an additional assessment of the influence of task specificity (contraction type) on fatigue in elderly adults. Moreover, the dorsiflexors differ from the quadriceps and therefore represent a model distinct from the isotonic fatigue protocol.
in young and old adults reported by Petrella and colleagues (19). For example, the proportion of FT muscle fibers is markedly lower in the dorsiflexors of both young and old adults (24% and 16%, respectively) (27) than in the quadriceps of young and old adults (50% and 45%, respectively) (28). Also, isometric strength of the quadriceps is decreased by as much as 40% in the 7th decade (19,29), but preserved at this age in the dorsiflexors (11,23,30) before weakening significantly by the beginning of the 9th decade (23,31). For this reason, a final novel feature of the present study is the inclusion of two groups of elderly adults to address the relative lack of knowledge with respect to the rate of change with aging (22).

Thus, the purpose of this study was to conduct an isotonic (velocity-dependent) fatigue experiment across one young and two elderly age groups using a muscle group that retains strength relatively well and possesses only a small proportion of FT muscle fibers (and thus, a potentially limited opportunity for age-related FT fiber atrophy or loss to exert a profound effect). As a result of these characteristics, we hypothesized that the dorsiflexors of young men and old men (~65 years) would have similar fatigue profiles during a velocity-dependent task. However, we expected that the substantial age-related changes that occur relatively late in life to the dorsiflexors would cause very old men (≥80 years) to experience increased fatigability as compared to young men.

**METHOD**

**Participants**

Twelve young men (aged 22–33 years), 12 old men (aged 60–69 years), and 12 very old men (aged 80–90 years) volunteered for this study. Young men were recruited from the university environment, and were considered to be recreationally active. Men in the two elderly groups were recruited from a local exercise program designed to maintain cardiovascular fitness, flexibility, and muscular endurance. All men were healthy with no evidence of neuromuscular disease. The mean age, height, and body mass of the three groups are reported in Table 1. The study was conducted in accordance with the guidelines for experimentation on humans established by the local university’s ethics review board, and informed, written consent was obtained from each of the 36 participants. Data were collected during the second of two visits to the neuromuscular laboratory; the first visit was to familiarize participants to the experimental procedures.

**Experimental Set-Up**

Both sessions (familiarization and test) were performed on the right leg in a Biodex multijoint dynamometer (System 3; Biodex Medical Systems, Inc., Shirley, NY). Participants sat in a reclined position with angles of approximately 90° at the hip and knee, respectively, and the leg was aligned parallel to the floor. An ankle angle of 25° of plantar flexion was used during isometric contractions. Dorsiflexion contractions performed in the isotonic mode began at this angle and ended at a neutral ankle position (0°) such that the range of motion was 25°. A Velcro strap across the right thigh, an adjustable seat belt across the waist, and shoulder straps minimized hip flexion and upper body movement. Velcro straps across the toes and the dorsum of the foot secured the limb to the dynamometer footplate.

Bipolar surface electromyography (EMG) signals were recorded from the tibialis anterior (TA) and the soleus muscles with self-adhering Ag/AgCl electrodes (1.5 × 1 cm; Kendall-LTP, Chicopee, MA). The skin was abraded and swabbed with alcohol before application of the electrodes. Using a 2 cm interelectrode distance, electrodes were placed in a longitudinal arrangement over the belly of the TA, and also on the soleus, distal to the medial head of the gastrocnemius.

**Experimental Procedures**

Baseline data collection began with the determination of the maximum twitch torque via supramaximal stimulation (100-μs pulse width) delivered over the common peroneal nerve, distal to the fibular head. The amplitude of the twitch was monitored as the current intensity was increased incrementally. When the torque reached a plateau, the current was increased a further 15% to be certain that stimulation was supramaximal. Subsequently, three isometric maximal voluntary contractions (MVCs) of the dorsiflexors were performed with 2 minutes of rest separating each attempt. Participants held each MVC for 3 seconds, during which time they were provided with visual feedback of torque via an oscilloscope, and received strong verbal encouragement. Voluntary activation was assessed on each MVC attempt by use of the interpolated twitch technique. The torque amplitude of a supramaximal twitch (T_s) delivered during the MVC was compared to a resting twitch (T_r) delivered after the MVC to quantify voluntary activation [% activation = \(1 - \left(\frac{T_s}{T_r}\right)\) × 100%].

After determination of the isometric MVC torque, the dynamometer was switched from the isometric to the isotonic mode. In this mode, one can program a resistance load that the dynamometer attempts to hold constant while velocity is measured throughout a range of motion. Current dynamometers are unable to maintain a constant load, so movements made in the isotonic mode are not strictly

<table>
<thead>
<tr>
<th>Group (N = 12)</th>
<th>Age (y)</th>
<th>Height (m)</th>
<th>Body Mass (kg)</th>
<th>Twitch Torque (Nm)</th>
<th>Twitch Duration (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young</td>
<td>25.9 ± 3.8</td>
<td>1.74 ± 0.06</td>
<td>77.5 ± 8.1</td>
<td>4.7 ± 1.3</td>
<td>188.2 ± 32.5</td>
</tr>
<tr>
<td>Old</td>
<td>64.3 ± 2.8</td>
<td>1.72 ± 0.07</td>
<td>83.3 ± 7.9</td>
<td>5.0 ± 0.6</td>
<td>217.1 ± 12.9</td>
</tr>
<tr>
<td>Very Old</td>
<td>83.7 ± 3.3</td>
<td>1.69 ± 0.05</td>
<td>74.9 ± 9.9</td>
<td>4.6 ± 1.2</td>
<td>264.5 ± 39.5*</td>
</tr>
</tbody>
</table>

*Note: Values are means ± standard deviations (twitch duration = time-to-peak torque + half-relaxation time). The twitch of the very old men had a significantly longer duration than that of the young and old men (*p < .05).*
isotonic (18). However, for the purposes of this study, the term isotonic will be used throughout the remainder of this article for this movement type. It is worth noting that this discrepancy is not relevant to the aim or results of this study because the movements are still velocity-dependent and therefore more applicable to physical function and aging than isometric or isokinetic movements. To determine maximum voluntary velocity at baseline, two contractions were completed at 20% MVC with 5 seconds of rest between each contraction. Participants received visual feedback of velocity via an oscilloscope and were instructed to contract as explosively as possible on each attempt. A 5-minute rest interval was provided between the baseline efforts and the fatigue protocol.

The fatigue protocol was designed to use a load that would be physically demanding but would still allow adequate range of motion to be maintained over a repeated number of contractions. Thus, the protocol involved 25 maximal isotonic contractions at 20% MVC performed at a rate of approximately one contraction every 1.6 seconds (i.e., the time required for the maximal voluntary effort and the footplate to fall passively to the starting position). Joint position was displayed on an oscilloscope and monitored by the investigator to ensure that participants did not experience a significant failure in the range of motion during the protocol. In the event that range of motion decreased by > 20% (from 25° to < 20°) on three consecutive efforts, the protocol was terminated regardless of whether the full complement of 25 contractions had been completed.

Data Processing and Statistics

Torque, velocity, and ankle position data were recorded by the Biodex at a sampling rate of 100 Hz. Using a 12-bit A/D converter (model 1401 Plus; Cambridge Electronic Design Ltd., Cambridge, U.K.), EMG (2500 Hz) as well as torque (100 Hz) and position (100 Hz) data were sampled online with Spike 2 software (version 4.13; Cambridge Electronic Design Ltd.). Peak values for isometric torque (Nm) and the isotonic velocity (rad/s) were recorded from the Biodex display during the baseline portion of the experiment. During offline analysis, the peak velocity (%/s) of each contraction during the fatigue portion of the experiment was recorded from the data stored on the Biodex. These peak velocity values were then used to calculate a mean value across five contractions (i.e., 1–5, 6–10, 11–15, 16–20, and 21–25) to separate the fatigue protocol into five sections. Power was calculated for the baseline contractions and during the fatigue protocol as the product of torque (Nm) and velocity (radians/s). Spike2 software was used to determine evoked twitch characteristics and agonist (TA) and antagonist (soleus) EMG during the fatigue protocol. Using ankle position, root-mean-square values of the EMG signals were calculated for the interval between the initiation of movement and the achievement of full range of motion.

Using SPSS software (version 11; SPSS, Inc., Chicago, IL), a univariate analysis of variance (ANOVA) was used to assess isometric MVC torque, twitch duration, as well as baseline measures of voluntary velocity and power at 20% MVC. Loss of power during the fatigue protocol was also assessed with a two-way repeated-measures ANOVA, with age as one factor and time (contraction number) as the other. All data are reported in the text as mean ± standard deviation, and the level of significance was p < .05. When a significant main effect or an interaction was found, Tukey’s honestly significant difference post hoc tests were performed to indicate where significant differences existed.

RESULTS

Isometric Baseline Measures

Although participants were of similar height and weight, the very old men were significantly weaker (32.7 Nm, SD 5.7) than both young (47.3 Nm, SD 5.6) and old men (44.8 Nm, SD 5.4), with no difference between the young and old men (Figure 1). Voluntary activation, as assessed by the interpolated twitch technique, was complete in each of the three age groups (data not shown). Maximal evoked twitch torque was similar across all age groups (Table 1). The contraction duration of the maximal evoked twitch was similar between young and old men, but was significantly prolonged (41% and 22% vs young and old men, respectively) in the very old men (Table 1).

Dynamic Baseline Measures

Maximal voluntary velocity values attained at 20% MVC were 175 °/s in young men, 154 °/s in old men, and 120 °/s in very old men. This finding reflected a significant and progressive reduction with age such that old men generated 12% less velocity than young men, and very old men produced 31% and 22% less than young and old men, respectively (Figure 1). Similarly, maximal power at 20% MVC was significantly lower in old than in young men (16%) and further reduced in the very old men, such that they produced 52% and 43% less power than young and old men, respectively (Figure 1). Maximal absolute power at
20% MVC was 28.7 W (SD 4.7) for the young men, 24.3 W (SD 4.6) for the old men, and 13.9 W (SD 4.0) for the very old men.

Fatigue

Range of motion was maintained throughout the entire fatigue protocol for all participants but one, an 87-year-old who completed only 11 of the 25 contractions before the protocol was terminated due to range of motion failure. Power loss during fatigue was significantly greater for very old men than for young men during the final 15 contractions of the protocol (Figure 2). Agonist EMG activity was well maintained throughout the protocol in all age groups (97%, 95%, and 96% of initial value for young, old, and very old men, respectively; Figure 3A). Antagonist EMG activity increased to a similar extent with fatigue in all age groups (111%, 113%, and 113% of initial value for young, old, and very old men, respectively; Figure 3B).

DISCUSSION

In accordance with our hypothesis, fatigability of the dorsiflexors during a velocity-dependent task increased with age. Following a moderate number of efforts at a relatively light load (25 contractions at 20% MVC), power loss was progressively greater with age; however, only the very old age group (≥80 years) was statistically more fatigable than the young adults. Agonist and antagonist EMG signals did not differ with age during the fatigue task, suggesting that neither reduced voluntary activation of the dorsiflexors nor increased coactivation of the plantar flexors contributed significantly to the increase in fatigue with advancing age.

The age-related impairment in endurance observed in this study is in contrast to the improvement in endurance recently reported for the dorsiflexors of old persons (72 years) during either an isometric or a concentric isokinetic task (11). However, our finding is similar to the decline in endurance recently reported for the dorsiflexors of old persons (77 years) during concentric and eccentric isokinetic tasks (12) and the knee extensors of old persons (64 years) during an isotonic task (19). The presence of conflicting or confirmatory results depending on the contraction type highlights the importance of task specificity in the study of fatigue across different age groups. Furthermore, the position of our results relative to those of each of these earlier studies would have been different without our very old age group; this emphasizes the value of incorporating more than one group of elderly adults.

Baseline Measures

Aged muscle undergoes losses of both strength and contractile velocity (19,20,22). The stationary nature of isometric tasks precludes any assessment of an age-related impairment in voluntary velocity, and thereby offers an incomplete assessment of the capacities of skeletal muscle (32). For example, old men generated ~12% less voluntary angular velocity than young men did during an isotonic effort at 20% MVC despite the fact that isometric strength and evoked twitch duration were unchanged. Thus, the impairment to velocity was the principal reason that old men produced 16% less muscle power than young men did.
at 20% MVC. In contrast, the 52% loss of power from the young to the very old men was due to equal 31% impairments in both strength and velocity. Losses of strength, velocity, and power between old and very old men were 27%, 22%, and 43%, respectively. Thus, it appears that strength is a greater contributor than velocity to power loss between the 7th and 9th decade. The progressive transition from velocity to strength impairments as the dominant contributor to power loss with advancing age is another example of the valuable information that can be obtained by including more than two groups in a cross-sectional study of aging.

Valour and colleagues (33) suggested that the velocity component of power is dependent on FT fibers. Our finding of losses in velocity and power in old men, without a significant decline in strength, may indicate that age-related changes to the FT fibers of the dorsiflexors between the 3rd and 7th decade are masked to some degree, or minimally impact performance, during isometric efforts. However, this is not the case in very old persons; the pronounced losses of velocity and power between the 7th and 9th decade are accompanied by a substantial loss of isometric strength and slowing of isometric contractile properties. The relative integrity of isometric measures into the 7th decade highlights two issues as it pertains to future experiments concerning age-related changes to the dorsiflexor muscle group. First, velocity-dependent (isometric) power tasks should be incorporated to obtain the most complete assessment of age-related changes. Second, whenever possible, elderly persons tested should be approaching 80 years of age to account for the well-preserved function of the muscle group.

Fatigue

Inclusion of a third group of men older than 80 years enabled us to document the anticipated loss of endurance during an isometric task with advancing age. However, unlike the findings from the quadriceps (19), we did not observe a significant increase in fatigability between participants aged ~25 years and those aged ~65 years. We believe that the discrepancy is likely the result of the different muscle groups tested and methodological differences concerning the isometric task. Age-related changes to the dorsiflexors are both smaller in magnitude and slower in progression than the changes that occur in the quadriceps (17). This result is most likely due to the nature of their use; that is, the decrease of high-intensity exercise that ordinarily accompanies the aging process will adversely affect the quadriceps more so than the dorsiflexors, which are used primarily for locomotion (34). A potentially important methodological difference between our study and that of Petrella and colleagues (19) was the load used to induce fatigue. Participants in the current study performed maximal isometric efforts at 20% MVC as opposed to the 40% MVC load used in the other study. As a result, our protocol involved a much higher number of contractions (25 vs 10, respectively) to obtain a similar loss of contractile velocity (~20%) in the participants aged ~65 years. It is worth noting that, although performing the same number of contractions as the 65-year-old participants, our young participants lost ~13% of their initial contractile velocity, whereas the young participants in the study by Petrella and colleagues (19) lost < 4%. This discrepancy might suggest that, despite the use of loads normalized to individual strength, repeated contractions with a heavy load is relatively easier for younger persons than for older persons. Moreover, despite the relatively lighter load used in our study, one of our oldest participants (87 years) was able to complete only 11 of the 25 contractions, which corroborates the suggestion of Cuoco and colleagues (14) that lighter loads are most applicable for testing power in very old persons. Use of light loads would be particularly important when testing adults older than 80 years from the general population because the increased fatigability of the very old participants in this study would be exacerbated in less fit individuals.

The possibility of velocity-dependent fatigue being influenced by an age-related decrease in agonist muscle activation or increase in coactivation of the antagonist muscle group has not been previously tested. Because the fatiguing task in the current study was isotonic in nature, superimposed stimulation procedures were not applicable for the assessment of voluntary activation (i.e., torque was approximately constant). Therefore, bipolar EMG signals were recorded from the TA and the soleus to assess agonist activation and antagonist coactivity, respectively, during the protocol. In all three groups, agonist and antagonist EMG during the final five contractions were between 95% and 97% and between 111% and 113%, respectively, of the values during the first five contractions. This finding suggests that neither a decrease in voluntary drive nor an increase in coactivity was responsible for the increase in fatigue with age, a finding similar to that of Baudry and colleagues (12), who reported that voluntary activation was maintained throughout fatigue in both young and old adults during concentric and eccentric isokinetic tasks. However, our young participants did have the highest level of agonist activity and the lowest level of antagonist activity at the completion of the fatigue protocol, which might suggest that significant differences could develop during a longer, more difficult fatigue task. Of minor note, during the fatigue protocol, agonist activity decreased whereas antagonist activity increased, which would suggest that cross-talk contamination of the EMG signals was minimal or absent.

Summary

These data suggest that there is a progressive age-related increase in fatigue from low-load isotonic dorsiflexion contractions. Because this contraction mode is more representative of the repetitive activities of daily living than either isometric or isokinetic tasks, any age-related impairment during repetitive velocity-dependent efforts are more likely to adversely affect functional mobility.

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REFERENCES


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