Age and load compliance alter time to task failure for a submaximal fatiguing contraction with the lower leg

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Submitted 15 December 2009; accepted in final form 12 March 2010

Griffith EE, Yoon T, Hunter SK. Age and load compliance alter time to task failure for a submaximal fatiguing contraction with the lower leg. J Appl Physiol 108: 1510–1519, 2010. First published March 18, 2010; doi:10.1152/japplphysiol.01396.2009.—The purpose of this study was to compare the time to failure and muscle activation of young and old adults for a sustained isometric submaximal contraction with the dorsiflexor muscles when the foot was restrained to a force transducer (force-control task) compared with supporting an equivalent inertial load unrestrained in the sagittal plane (position-control task). Seventeen young (23.6 ± 6.5 yr) and 12 old (70.0 ± 5.0 yr) adults performed the force-control and position-control tasks at 30% maximal voluntary contraction (MVC) until task failure on separate days. Despite the similar load torque for each task, time to failure was longer for the force-control than position-control task (10.4 ± 4.5 vs. 8.6 ± 3.4 min, \(P = 0.03\)) for the young and old adults. The old adults, however, had a longer time to task failure than the young adults for both tasks (11.4 ± 4.4 vs. 8.1 ± 2.1 min, \(P = 0.01\)), with no interaction of age and task (\(P = 0.83\)). The rate of increase in agonist and antagonist root-mean-square EMG, agonist EMG bursting activity, mean arterial pressure, and heart rate during the fatiguing contraction was greater for the position-control than force-control task for the young and old adults. The old adults had a less rapid rate of increase in EMG activity, fluctuations in motor output, and cardiovascular measures than the young adults for both tasks. Development of fatigue can be manipulated in young and old adults by providing greater support to the foot and less ankle compliance during daily and ergonomic tasks that require prolonged activation of the lower leg. Minimizing load compliance to one degree of freedom during a position-control task maintained the greater fatigue resistance with age for an isometric contraction.

Because of the heightened reflex responsiveness during the more unstable task compared with the control of force (1). Consequently, increasing foot stability during a position-control task by minimizing the degrees of freedom at the ankle joint while supporting an inertial load with the lower leg decreased muscle fatigability and altered activation of the primary agonist in young adults (53).

The influence of aging on the control of position during a fatiguing contraction is not known but important to understand because of the age-related decrements in postural control of the lower limb that are associated with greater risk of falling in old adults (38, 47, 52). Aging is accompanied by changes in the neuromuscular system that potentially influence the time to failure and physiological adjustments during a fatiguing task, particularly when the load is not stable. For isometric force-control tasks, old adults are usually more fatigue-resistant than young adults (20, 21, 29, 35) because of an age-related loss and change in motor units that lead to a greater reliance on oxidative metabolism and a slowing of contractile properties with age (8, 10, 25, 29, 30). In contrast, old adults have decreased excitability of the motor neuron pool compared with young adults (9, 12, 13, 32, 50), which potentially limits performance of a fatiguing contraction (7, 26, 32), especially when the requirements of the task involve greater adjustments within spinal or supraspinal centers, as for control of position while supporting an inertial load. Accordingly, old adults can have a reduced ability to modulate reflexes of the lower leg compared with young adults (9, 11, 13, 31, 43, 51). Furthermore, control of position involves greater modulation of reflexes than does force control (1), which can be impaired with age (2). Thus the mechanisms contributing to the briefer time to task failure for a position-control than force-control task may differ with advanced age, influencing the magnitude of the task difference. Although old adults were shown to have a briefer time to task failure for a position-control than force-control task with the elbow flexor muscles (23), the impact of age on performance of position control is not clear, because there was no young control group.

The influence of age on the fatigability of a task that requires position control with lower limb muscles that are important for postural control is not known. The purpose of this study, therefore, was to compare the time to failure and muscle activation of young and old adults for a sustained isometric submaximal contraction with the dorsiflexor muscles when the foot was supported and restrained to a force transducer (force-control task) compared with supporting an equivalent inertial load unrestrained in the sagittal plane (position-control task). Because there is greater demand of reflex responsiveness during position control than force control (1), which can be impaired with age (2), we hypothesized that the difference in time to task failure for a position-control task compared with a

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force-control task would be greater for old than young adults for the lower leg muscles.

METHODS

Seventeen young adults (8 men and 9 women; mean ± SD: 23.6 ± 6.5 yr, 167.0 ± 9.6 cm, 65.8 ± 12.0 kg) and 12 old adults (7 men and 5 women; mean ± SD: 70.0 ± 5.0 yr, 170.2 ± 11.4 cm, 78.2 ± 18.2 kg) volunteered to participate in the study. All subjects were healthy, with no known neurological, musculoskeletal, or cardiovascular disease. Before participation, each subject provided informed consent, and the protocol was approved by the Institutional Review Board at Marquette University. The physical activity level for each subject was assessed with a questionnaire (34) that estimated the relative kilocalorie expenditure of energy per week.

Subjects reported to the laboratory on three separate occasions: once for a familiarization session and two additional times for the experimental sessions, which involved fatiguing contractions of the dorsiflexor muscle group of the nontandominant foot. Dominance was determined as the preferred kicking foot. During the familiarization session, subjects practiced maximal voluntary contractions (MVCs) of the dorsiflexor, knee extensor, and plantar flexor muscle groups.

The two experimental sessions involved a fatiguing contraction of the dorsiflexor muscle group. During one experimental session, subjects maintained a force that was equivalent to 30% MVC force for as long as possible; this is referred to as the force-control task. During the other experimental session, subjects maintained a neutral ankle angle while supporting an inertial load equivalent to 30% MVC force; this is referred to as the position-control task. The two experimental sessions were separated by ≥5 days, and the order was counterbalanced among the subjects and groups. The load torque was identical for each subject across the two sessions. Subjects were provided with visual feedback during both tasks: the force exerted by the dorsiflexors during the force-control task and ankle angle during the position-control task. For both tasks, the subject was required to sustain the fatiguing contraction for as long as possible.

**Mechanical Recording**

Subjects were seated in an adjustable chair (Biodex Medical Systems), with the hip and knee at 90° of flexion. The nontandominant foot was assessed with the ankle in a neutral position (0° dorsiflexion) and placed on an aluminum footplate within a custom-designed dynamometer (Romus, Milwaukee, WI) that allowed measurement of dorsiflexion isometric forces (force-control) and performance of the position-control task by a quick release of the footplate from the force transducer (model SBO-200, Transducer Techniques, Temecula, CA).

The footplate was adjustable for height and foot length and was mounted on a rigid steel vertical brace that was securely anchored to the floor. The subject’s foot was secured to the footplate with two straps over the most distal aspect of the dorsum of the foot and the center distance between each electrode pair was 20 mm. Reference electrodes on each muscle were placed according to the European AgCl electrodes (8 mm diameter) were used for the bipolar surface EMG recordings. Electrodes were taped to the skin inline with the fiber direction and over the belly of each muscle. The recording electrodes on each muscle were placed according to the European Recommendations for Surface Electromyography (18). The center-to-center distance between each electrode pair was 20 mm. Reference electrodes were placed on the medial malleolus for the tibialis anterior, gastrocnemius, and soleus muscles and on the patella for the rectus femoris. All EMG signals were amplified (1,000 times), band-pass filtered (3–1,000 Hz), and recorded to a personal computer via Power 1401 and Spike2 software. The EMG was sampled at 2,000 samples/s and analyzed offline using Spike2 software.

**Cardiovascular Measurements**

Heart rate and blood pressure were monitored throughout the fatiguing contraction with an automated beat-by-beat blood pressure monitor (Finapress 2300, Ohmeda, Louisville, CO). The cuff was placed around the middle finger of the left hand, and the arm was placed with the hand at heart level. The blood pressure and heart rate were sampled at 500 samples/s and collected online to a computer using Spike2 software.

**Experimental Protocol**

Each of the two experimental sessions involved the same core procedures. They included performance of 1) MVCs of the knee extensor and ankle plantar flexor muscles to obtain peak EMG values for the rectus femoris, soleus, and medial gastrocnemius muscles; 2) MVCs of the dorsiflexor muscles to obtain maximal isometric strength and peak EMG values; 3) submaximal contractions of the dorsiflexor muscles while attached to the force transducer (force-control task) to assess the EMG-force relation on each experimental day; 4) a fatiguing contraction of the dorsiflexor muscles at 30% MVC with the dorsiflexor muscles (force-control or position-control task); and 5) an MVC with the dorsiflexor muscles (within 10 s of task termination).

MVCs of the knee extensors and plantar flexor muscles. MVCs of the knee extensor and plantar flexor muscles were obtained at the beginning of each experimental session to obtain peak EMG. Two MVCs were performed with the knee extensor muscles followed by two MVCs of the plantar flexor muscles. Subjects rested for 60 s between each trial. For both muscle groups, the MVCs were performed in the posture and leg position described above for the fatiguing contraction of the dorsiflexor muscles. Knee extension and
plantar flexion forces were not recorded during these contractions. Each subject, however, was asked to push as hard as possible against the immovable restraint for 3–4 s. For the knee extensor muscles, an inflexible strap was attached between the chair and the leg (just above the lateral malleolus), so that the lower leg was restrained at 90° of flexion when the subject performed maximal knee extension. For the plantar flexor muscles, the foot of each subject was placed on the footplate, and vertical movement was minimized during each MVC by an inflexible strap that was placed just proximal to the knee anchored to the floor. The largest EMG activity from these MVCs was used to normalize the EMG recordings during the fatiguing contractions of the rectus femoris, medial head of the gastrocnemius, and soleus muscles.

**MVC force of the dorsiflexor muscles.** Subjects performed four MVC trials with the ankle dorsiflexors while their foot was attached to the force transducer. Each subject was asked to increase the force exerted from zero to maximum over 1–2 s, with the maximal force held for 2–3 s. Subjects were given visual feedback on a monitor and were given strong verbal encouragement to achieve and maintain maximal force. Subjects rested for 60 s between each trial. If the peak force achieved for two of the four trials was not within 5% of each other, additional trials were performed until this criterion was met. The greatest force achieved over the trials was taken as the MVC and used for calculations of the submaximal target forces and the inertial load used for the position task.

**EMG activity during submaximal tasks.** The EMG activity of the involved muscles was recorded in standardized tasks, so that the force-EMG relation could be compared across experimental days. For the dorsiflexor muscles, the subject performed an isometric contraction for 6 s at target forces of 20, 40, and 60% MVC, with 60 s of rest between each contraction. The order of the contractions was randomized for each subject and remained constant for each subject on the two experimental days.

**Fatiguing contractions.** The subject was required to match the target force as displayed on the monitor for the force-control task and was verbally encouraged to sustain the force for as long as possible. The fatiguing contraction was terminated when the force declined by 5% of the target torque, despite strong verbal encouragement to maintain the task. This time was recorded as the time to task failure for the force-control task. The position-control task was terminated when the ankle angle declined by 18° from a right angle, despite strong verbal encouragement. The footplate moved in the sagittal plane only and did not allow for inversion or eversion of the ankle. In most circumstances, the position-control task was ended with the subject dropping the load abruptly at task failure. This time of termination was recorded as the time to task failure for the position-control task. On the basis of a static biomechanical analysis, the two criteria for task termination represented similar changes in the load torque about the ankle joint for the two tasks. To minimize the influence of transient fluctuations in motor output on the criteria for task failure, the task was terminated only after torque fell below the predetermined threshold for 4 consecutive seconds. Neither the subject nor the investigator who terminated the task knew the time during the tasks. Subjects were not informed of the time to task failure until they completed their final experimental session. An index of perceived effort, the rating of perceived exertion (RPE), was assessed with the modified Borg 10-point scale. The subject was instructed to focus the ratings of exertion on the dorsiflexor muscles. The scale was anchored so that 0 represented the resting state and 10 represented the strongest contraction that the muscles can perform. RPE was recorded at 60-s intervals during the fatiguing contraction.

**Data Analysis**

All data collected during the experiments were recorded online using a Power 1401 A/D converter and analyzed using Spike2 software. The MVC force was quantified as the average value over a 0.5-s interval that was centered about the peak. The maximal EMG for each muscle was determined as the root-mean-square (RMS) value over a 0.5-s interval about the peak EMG during the MVC. The RMS EMG value of the 6-s submaximal contractions for the tibialis anterior performed at 20, 40, and 60% MVC torque was averaged over the middle 2 s during the 6-s contraction. RMS EMG values of the tibialis anterior, medial gastrocnemius, soleus, and rectus femoris were quantified during the fatiguing contraction performed at 30% MVC force at the following time intervals: the first 30 s; 15 s on both sides of 25, 50, and 75% of time to task failure; and the last 30 s of the task duration. The EMG activity of each muscle was normalized to the EMG value obtained during the MVC for each respective muscle group. The level of coactivation was quantified during the fatiguing contractions by calculating the ratio of the RMS EMG (%peak) of the agonist muscle (tibialis anterior) to that of the antagonist muscles (medial gastrocnemius or soleus) (27, 36).

To quantify the bursts of EMG activity of the tibialis anterior, the EMG signal was rectified, smoothed (average of 1-s duration, 500 data points), and then differentiated over 0.25-s averages. The differentiated signal represents the rate of change and was used to identify rapid changes in the rectified smoothed EMG signal. A threshold for establishing if a burst of EMG had occurred was determined by first determining the minimum SD of the differentiated EMG during the fatiguing contraction using a 30-s moving window. The threshold for a burst was then defined as the mean ± 3 SD of the minimum differentiated signal. The minimal burst duration was 0.1 s. The EMG bursting activity (bursts/min) was quantified for five continuous intervals of 20% of the time to task failure.

The fluctuations in force during the force-control task and in acceleration during the position-control task were quantified for the first 30 s; 15 s on both sides of 25, 50, and 75% of time to task failure; and the last 30 s of the task duration. The amplitude of fluctuations in motor output was quantified as the SD of force for the force-control task and the SD of acceleration for the position-control task.

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

**Statistical Analysis**

Values are reported as means ± SD in the text and displayed as means ± SE in Figs. 1–5. Separate two-way mixed ANOVAs (age × task) were used to compare the time to task failure, percent decline in MVC force, and rates of increase in various dependent variables (normalized to absolute time) across the two tasks (force-control vs. position-control) and two age groups (young vs. old). Separate three-way mixed ANOVAs (age × tasks × time) were used to compare the dependent variables of MVC force, heart rate, MAP, RPE, relative change in fluctuations in motor output, and EMG burst rate for the tibialis anterior and RMS EMG activity during the fatiguing contractions of the various muscles. EMG-force relations for the 6-s constant-force contractions were analyzed using ANOVA with repeated measures on task and intensity (with age as a between-group factor). Post hoc analyses (Tukey-Kramer) were used to test for differences among pairs when appropriate. A significance level of P < 0.05 was used to identify statistical significance.

The contribution of several variables to the time to task failure was analyzed using stepwise multiple regression analysis for the force-control and position-control tasks separately and also for the difference in time to failure between the two tasks. Those variables that were significantly correlated (using Pearson’s product-moment correlation coefficient) with time to task failure were selected as predictors.
There was no interaction of task and age (briefer than force-control task for young and old adults (task effect, young adults for both tasks (age effect, young adults for both sessions (intensity × session, old adults had a longer time to task failure for the forward-control than position-control task.

**RESULTS**

Step regression analysis was performed with all significantly correlated variables entered and then again with only EMG variables as predictors. Only predictors that had significant ($P < 0.05$) partial effects were reported for the final regression model. The individual contribution of each predictor was reported as the squared semipartial correlation coefficient.

**EMG Force Relation**

The EMG activity (RMS, %peak EMG) for the tibialis anterior muscle was determined during brief isometric contractions held at 20%, 40%, and 60% MVC for young and old adults during both testing sessions prior to the fatiguing contraction. EMG activity increased with contraction intensity (contraction intensity effect, $P < 0.001$) similarly for both testing sessions and age groups (intensity × session, $P = 0.46$; Table 1). There was no difference between sessions (days) for young and old adults (session effect, $P = 0.12$). The old adults, however, exhibited greater EMG activity at the lower intensities of contraction than the young adults (intensity × age, $P = 0.01$) across both sessions (session × intensity × age, $P = 0.52$).

**EMG Activity During the Fatiguing Contraction**

**EMG Activity of the Tibialis Anterior.** EMG activity (RMS, %peak EMG) for the tibialis anterior muscle in young and old adults increased during the fatiguing contraction for both tasks and age groups (time effect, $P < 0.001$; Fig. 2A). EMG activity was greater for the position-control (35 ± 13%, pooled for time and age) than force-control (28 ± 22%: task effect, $P < 0.001$) task. Furthermore, the rate of increase in EMG was greater for the position-control than force-control task (2.8 ± 22 vs. 1.9 ± 1.7%/min, $P < 0.01$) for young and old adults (task × time × age, $P = 0.49$). The rate of increase in EMG activity for the force-control and position-control tasks was more rapid for the young than old adults (2.7 ± 1.9 vs. 1.3 ± 0.8%/min, $P < 0.01$).

**EMG Bursting Activity of the Tibialis Anterior.** There was a progressive increase in number of bursts per minute in EMG activity during both tasks (time effect, $P < 0.001$; Fig. 2B). The bursting activity increased at a greater rate for the position-control than force-control task ($0.38 ± 0.18 vs. 0.27 ± 0.22 bursts-min⁻¹-min⁻¹; task × time, $P = 0.007$) for young and old adults. The bursting activity increased at a greater rate for the young than old adults ($0.42 ± 0.18 vs. 0.19 ± 0.17 bursts-min⁻¹-min⁻¹) for both tasks (time × age, $P = 0.003$).

**Table 1. RMS EMG activity of a force-control task at various intensities of MVC performed at each experimental session prior to fatiguing contraction**

<table>
<thead>
<tr>
<th>Contraction Force</th>
<th>Force-Control Session</th>
<th>Position-Control Session</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Young</td>
<td>Old</td>
</tr>
<tr>
<td>15% MVC</td>
<td>10.8 ± 3.8</td>
<td>15.8 ± 3.5</td>
</tr>
<tr>
<td>30% MVC</td>
<td>19.2 ± 7.6</td>
<td>25.9 ± 5.7</td>
</tr>
<tr>
<td>45% MVC</td>
<td>31.1 ± 9.8</td>
<td>35.8 ± 6.4</td>
</tr>
<tr>
<td>60% MVC</td>
<td>44.9 ± 10.5</td>
<td>47.0 ± 8.5</td>
</tr>
</tbody>
</table>

Values are means ± SD, expressed as percentage of peak EMG during maximal voluntary contraction (MVC). RMS, root mean square. There was no difference between sessions (days) for young and old adults ($P > 0.05$). EMG activity was greater for old than young adults at lower intensities for both sessions (intensity × age, $P = 0.01$).

**Fig. 1. Time to task failure of young and old adults for force-control and position-control tasks.** Time to failure (mean ± SE) was longer for old than young adults for both tasks (age effect, $P = 0.01$). Position-control task was briefer than force-control task for young and old adults (task effect, $P = 0.03$). There was no interaction of task and age ($P = 0.83$).
EMG Activity of Antagonist and Accessory Muscles

Gastrocnemius. EMG activity (RMS, % peak EMG) of the gastrocnemius increased during both fatiguing tasks for young and old adults (time effect, $P < 0.001$; Fig. 3A). EMG activity increased more rapidly for the position-control than force-control task (task $\times$ time, $P < 0.001$) for young and old adults. The rate of increase in EMG (normalized to absolute contraction (%MVC) peak) for force-control and position-control tasks. Each data point represents mean $\pm$ SE at 25% increments of time to task failure for a 30-s interval. EMG activity and rate of increase in EMG were greater for position-control than force-control task ($P < 0.01$) for young and old adults. Rate of increase in EMG activity was more rapid for young than old adults for force-control and position-control tasks ($P < 0.01$). B: burst rate of the EMG signal for the tibialis anterior for the fatiguing contractions. Values are means $\pm$ SE at 20% intervals of time to task failure. Increase in burst rate was greater for position-control than force-control task for young and old adults ($P = 0.007$). Bursting activity increased at a greater rate for young adults for both tasks ($P = 0.003$).

Coactivation of the gastrocnemius increased during the fatiguing contractions (time effect, $P = 0.02$) but differently across the tasks (time $\times$ task, $P = 0.01$). Coactivation of the gastrocnemius increased from the start to the end of the position-control task (from 0.72 $\pm$ 0.42 to 0.88 $\pm$ 0.47), with minimal increases during the force-control task (from 0.77 $\pm$ 0.40 to 0.81 $\pm$ 0.41). For both tasks, there was a suggestion of greater coactivation at the start of the contraction for the old than young adults (0.86 $\pm$ 0.34 vs. 0.66 $\pm$ 0.44) and similar activation at the end (0.88 $\pm$ 0.34 vs. 0.82 $\pm$ 0.50, respectively), but this did not reach statistical significance (time $\times$ age, $P = 0.08$). There was no interaction for age, task, and time ($P = 0.97$).

Soleus. EMG activity of the soleus increased over time during both tasks ($P < 0.001$; Fig. 3B). The rate of increase in EMG activity was greater during the position-control task (task $\times$ time, $P = 0.002$), but this was similar for young and old adults ($P = 0.78$). Coactivation ratios for the soleus mirrored those of the gastrocnemius. Coactivation levels increased during the fatiguing contractions, but at lesser rates during the force-control (from 0.91 $\pm$ 0.47 to 0.99 $\pm$ 0.61) than position-control (from 0.78 $\pm$ 0.44 to 1.01 $\pm$ 0.57; time $\times$ task, $P = 0.01$ task).

Rectus femoris. EMG activity of the rectus femoris increased during both fatiguing tasks for young and old adults (time effect, $P < 0.001$; Fig. 3C). As for the antagonist muscles, the rate of increase in rectus femoris EMG activity was greater for the position-control than force-control task (task $\times$ time, $P = 0.014$). There was no difference with age ($P = 0.20$), nor were there any other interactions.

MAP and Heart Rate

MAP increased during both tasks for young and old adults ($P < 0.001$; Fig. 4A). Although MAP reached similar values at

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Fig. 2. EMG activity and EMG bursting activity of the tibialis anterior of young and old adults during fatiguing contractions for force-control and position-control tasks. A: root-mean-square (RMS) EMG (percent maximal voluntary contraction (%MVC) peak) for force-control and position-control tasks. Each data point represents mean $\pm$ SE at 25% increments of time to task failure for a 30-s interval. EMG activity and rate of increase in EMG were greater for position-control than force-control task ($P < 0.01$) for young and old adults. Rate of increase in EMG activity was more rapid for young than old adults for force-control and position-control tasks ($P < 0.01$). B: burst rate of the EMG signal for the tibialis anterior for the fatiguing contractions. Values are means $\pm$ SE at 20% intervals of time to task failure. Increase in burst rate was greater for position-control than force-control task for young and old adults ($P = 0.007$). Bursting activity increased at a greater rate for young adults for both tasks ($P = 0.003$).

Fig. 3. EMG activity of medial gastrocnemius (GA; A), soleus (Sol; B) and rectus femoris (RF; C) during fatiguing contractions of young and old adults for force-control and position-control tasks. Values are means $\pm$ SE at 25% increments of time to task failure for a 30-s interval. RMS EMG (%peak) of GA, Sol, and RF increased at a greater rate for position-control than force-control task ($P < 0.05$) similarly for young and old adults.
adults started and ended the tasks at similar values (Fig. 4C). When rates of increase were compared, the task effect was \( P = 0.07 \), and the task \( \times \) age interaction was \( P = 0.05 \). Although not statistically significant, these results suggest a greater rate of increase in RPE during the position-control than force-control task, especially for the young adults (task \( \times \) age, \( P = 0.05 \)).

**Fluctuations in Force and Acceleration During the Fatiguing Contraction**

The amplitude of the vertical fluctuations in force and acceleration increased progressively during the two tasks (time effect, \( P < 0.001 \); Fig. 5). The rate of increase in the acceleration fluctuations during the position-control task was similar to the increase in force fluctuations during the force-control task (task \( \times \) time, \( P = 0.34 \); Fig. 5). The increase in fluctuations, however, was less for the old than young adults (age effect, \( P < 0.001 \); time \( \times \) age, \( P = 0.003 \)) for the force-control and position-control tasks.

**Factors That Contributed to Time to Failure: Stepwise Regression Analysis**

Regression analysis indicated that the rate of change in RPE was the most significant predictor of time to failure for the force-control and position-control tasks (Table 2). Rate of increase in RPE explained 70% and 25% of variance in the time to task failure for force-control and position-control tasks, respectively. Similarly, regression analysis showed that the difference in the rate of change in RPE between the two tasks explained 62% \((r^2 = 0.62)\) of the difference between the time to failure of the force-control and position-control tasks, and there were no other predictors. These results indicate that the greater the difference (reduction) in the time to task failure from the force-control task to the position-control task, the more rapid was the rise in RPE during the position-control task compared with the force-control task.

When only the EMG-related variables were entered into the analysis for the tasks separately, the rate of change in tibialis anterior EMG explained 27% of variance in the time to task failure for the force-control task and the rate of change in EMG

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**Perceived Exertion During the Fatiguing Tasks**

RPE increased during the force-control and position-control tasks for young and old adults \( (P < 0.001) \). Young and old adults started and ended the tasks at similar values (Fig. 4C). When rates of increase were compared, the task effect was \( P = 0.07 \), and the task \( \times \) age interaction was \( P = 0.05 \). Although not statistically significant, these results suggest a greater rate of increase in RPE during the position-control than force-control task, especially for the young adults (task \( \times \) age, \( P = 0.05 \)).

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bursting activity of the tibialis anterior explained 51% of the variance for the position-control task (Table 2).

**DISCUSSION**

The novel findings of the study were that young and old adults exhibited a briefer time to failure during a position-control task (limited to 1 degree of freedom) than during a force-control task for a submaximal isometric contraction with the ankle dorsiflexor muscles. Aging did not alter the difference in time to failure between the force-control and position-control task for the ankle dorsiflexor muscles. The briefer time to failure when the foot was required to control the position of an inertial load during dorsiflexion was accompanied by more rapid rates of increase in EMG agonist and antagonist activity, EMG bursting activity, and cardiovascular measures compared with the more stable force-control task for both age groups. Accordingly, perceived effort (RPE) for the same load increased at a greater rate during the position-control than force-control task for young and old adults and was the main predictor of the difference in time to failure between the tasks. The old adults, however, had a longer time to task failure than the young adults for both tasks, and this was accompanied by a slower rate of rise in EMG activity (RMS and bursting), cardiovascular measures, and fluctuations in motor output with age. Thus, minimizing load compliance to one degree of freedom during a position-control task maintained the greater fatigue resistance with age for an isometric task.

The time to task failure was briefer for the position-control task for young and old adults, indicating that motivation and effort were similar at task failure across both tasks.

**Task Differences Were Similar With Age**

The difference in time to failure between the force-control and position-control task with the lower leg muscles was similar for the young and old adults (~17%). We expected a larger difference in time to failure between the two tasks with increased age, because old adults can show a reduced ability to modulate reflexes of the lower leg compared with young adults (9, 11, 13, 31, 43, 51). The control of position involves greater modulation of reflexes than force control (1), which can be impaired with age (2). Aging, however, did not influence the development of fatigue more during control of position than control of force with the dorsiflexor muscles in the lower limb. Because reported levels of physical activity in our sample were similar for the old and young adults, we can attribute our results for a lack of age difference in time to failure between the tasks to age, rather than an age-related difference in physical activity.

One possibility for the similar difference in time to failure between tasks with age was the relative stability of the position-control task in this study. In contrast to our previous study with the ankle dorsiflexor muscles in young adults (27), the position-control task was relatively stable, because support was provided under the foot and load compliance was limited to one degree of freedom that was in the sagittal plane only. In young adults, increasing foot stability during a position-control task by minimizing the degrees of freedom at the ankle joint decreased muscle fatigability and also altered activation of the primary agonist in young adults (53). Consequently, for young adults, the difference in time to failure between the force-control and position-control task was less in the present study (20%) than in previous studies (27, 53), in which there was less

<table>
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<th></th>
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Predictors that were significantly correlated with the time to task failure were entered into the analysis. Rate_RPE, rate of increase in rating of perceived exertion (RPE); RPE_end, RPE at the end of the fatiguing contraction; Rate_TA, rate of increase in tibialis anterior EMG; Rate_BA, rate of increase in EMG bursting activity of the tibialis anterior; sr², squared semipartial correlation coefficient.

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support under the foot during the position-control task (53%). Accordingly, in contrast with our other studies when the inertial load was less stable during the position-control task (3, 24, 27, 48), the fluctuations in motor output in the present study did not differ between the force-control and position-control tasks. An age difference in the time to failure between the force-control and position-control task could possibly be expressed when old adults are more challenged with a less stable position-control task that requires greater adjustments of the inertial load. An additional consideration is that the tasks were performed at a slightly higher intensity in the present study than in previous studies (27, 53) (30%, rather than 20%), which may also have contributed to the lesser task differences (40). Nevertheless, the compliance differed enough between the force-control and position-control tasks to alter performance for young and old adults, although less than previously observed for the dorsiflexion tasks (27).

Young and old adults used similar strategies to adjust to the more compliant load. An important finding was that indicators of neural activity during the control of position increased at a greater rate than during the control of force for young and old adults. Accordingly, the most significant predictor of the variability in the time to task failure (tasks and age groups pooled) was RPE. In another study, perceived effort was also a significant predictor of time to failure for the ankle dorsiflexion of both tasks performed by young adults when the requirement was to control the position of a load with little restraint (27). Because perceived effort is modulated by descending drive (6, 41), the data provide evidence that a difference between the position-control task in the present study and the force-control task likely involves mediation of central processes.

EMG activity and bursting activity of the primary agonist muscle, the tibialis anterior, also increased at a greater rate during the position-control than force-control task. Accordingly, when only EMG variables from each muscle were considered, the main EMG predictor of the time to failure for the force-control task was the rate of increase in tibialis anterior EMG, and for the position-control task it was the EMG burst rate of the tibialis anterior. The greater rate of increase in EMG of the agonist muscle(s) was also observed for various muscle groups in young adults (3, 27, 40, 49). The greater EMG activity and rate of increase in EMG activity were not due to recording conditions, because EMG was similar across experimental days for the brief submaximal contractions at varying intensities for both age groups. The difference in EMG activity between the tasks represents a greater rate of motor unit recruitment and change in discharge rate during the position-control task compared with the more stable force-control task (3, 44). Evidence suggests that for young adults the greater rate of excitation of the motor unit pool may have involved a reduced Ia presynaptic inhibition during control of position compared with the control of force because of the heightened reflex responsiveness during the more unstable position-control task (1). This increased excitation during the more unstable task was indicated by the primary role of the rate of EMG bursting activity of the tibialis anterior in predicting the time to task failure of the position-control task. Age, however, did not appear to significantly alter the EMG adjustments between the two tasks. Although the EMG activity of the tibialis anterior muscle was greater for old adults at the start of the force-control task than for the young adults (see Table 1 for EMG activity for the 6-s force tasks and Fig. 2), this did not markedly affect the task difference in time to failure with age. The rate of increase in EMG activity for both tasks was lower for the old than young adults, but the task difference was maintained toward task failure. These results suggest that the mechanisms for the greater rate of motor unit recruitment during the control of position, possibly Ia presynaptic inhibition (1, 2, 4, 43), did not differ with age between a relatively stable position-control task (limited to 1 degree of freedom) and a force-control task.

The increased rates of EMG were accompanied by more rapid rates of antagonist activation (medial gastrocnemius and soleus) during the fatiguing contractions when controlling for position of the load compared with the more stable force-control task. There was marked activation of the antagonist muscles during both tasks compared with other muscles and setups (24, 27, 40) that can be attributed to this specific setup for the ankle dorsiflexor muscles. The large activation of the antagonist muscles suggests that young and old adults may have stabilized the heel against the footplate during dorsiflexion. The greater rate of increase in coactivation during the control of position, however, may have provided additional stability at the ankle during the position-control task, minimizing any difference between tasks in fluctuations of motor output. Accordingly, the fluctuations in motor output did not differ between the force-control and position-control tasks (Fig. 5). These findings are in contrast to the typical observation of a greater rate of increase in motor output fluctuations during less stable position-control tasks for lower leg and upper limb muscles (3, 24, 27, 48). Rather, age had a much greater influence on the development of fluctuations in motor output than task during the fatiguing contractions.

The rates of rise in other physiological measures, including MAP and heart rate, increased more rapidly during the position-control than force-control task. The rates of rise in MAP, heart rate, and RPE, however, showed less differences between the tasks than previously observed for the tibialis anterior and upper limb muscles (23, 24, 27). The increase in heart rate is modulated by central command (14–16), and MAP is driven by both central command and peripheral reflexes (metaboloreflex) during isometric fatiguing contractions (group III and IV afferent feedback) (42, 46). The greater stability of the inertial load during the position-control task in this study than in our previous study (27) may have also resulted in less difference between the tasks in the adjustment of heart rate and MAP. Other factors that may have diminished the differences in cardiovascular measures between tasks are the higher-intensity contraction required (30% MVC) and the increased antagonist activation relative to that typically observed (24, 27, 40). Both of these factors involve greater muscle activation of the available muscle in the lower leg, which will ultimately influence heart rate and MAP.

Old Adults Had a Longer Time to Failure for Both Tasks

The old adults had a longer time to task failure than the young adults for the force-control and position-control tasks (~29% difference). Thus the age difference often observed for an isometric fatiguing contraction controlled for force (19, 29) was similar for the position-control task with the more compliant load when restricted to one plane of compliance. Ac-
Accordingly, both tasks for the old adults showed a reduced rate of increase in most physiological variables (EMG activity, EMG bursting activity, fluctuations in motor output, heart rate, and MAP) during the fatiguing contractions compared with the young adults. These slower rates of increase reflect age-related changes in the motor unit pool and muscle. For isometric tasks, a large contributor to the greater fatigue resistance in old adults is a more oxidative profile of old muscle that has slower contractile properties (8, 19, 29). Old adults, for example, can possess a greater proportion of type I area than young adults in large muscles (25, 28, 33) because of selective atrophy of type II fibers (25) and an age-related loss of motor units (5, 10, 37). Consequently, old adults exhibit slower contractile properties, such as reduced peak rates of contraction and relaxation force of the muscle and a shift to the left in the force-frequency curves, so that fusion of a contraction can occur at a lower discharge rate for the tibialis anterior (8, 30) and other muscles (25, 33, 45). Thus, motor unit recruitment and EMG activity were less rapid with age, probably because the active motor units were able to maintain the required torque for a longer duration. Accordingly, the increase in MAP was also less rapid, probably because metabolite buildup in the target muscle was less and there was less group III and IV feedback to cardiovascular regulatory centers in the brain stem (17, 42, 46). These less rapid rates of increase in physiological variables for the old than young adults were apparent during both isometric tasks. The greater compliance in the sagittal plane during control of position, therefore, did not compromise the increased fatigue resistance with age.

In summary, fatigability of the dorsiflexors muscles increased similarly with age for a position-control task (with compliance restricted to the sagittal plane) compared with a force-control task for a submaximal isometric contraction sustained with the dorsiflexor muscles. The mechanisms contributing to briefer time to failure for a position-control task were likely similar for the young and old adults, because task differences in the physiological adjustments did not change with age. Furthermore, the age differences in time to failure often observed for a submaximal isometric force-control task were maintained for a position-control task with the lower leg. Healthy old adults, therefore, have similar potential to that of young adults in manipulating fatigue to overload the neuromuscular system for effective rehabilitation by varying limb support and the stability of the load. Conversely, fatigue can be minimized in young and old adults during daily and ergonomic tasks that require prolonged activation of the lower leg by providing greater support to the foot with a less compliant load.

GRANTS

This study was supported by an American College of Sports Medicine predoctoral award to E. E. Griffith.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

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