Older adults are less steady during submaximal isometric contractions with the knee extensor muscles

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Tracy, Brian L., and Roger M. Enoka. Older adults are less steady during submaximal isometric contractions with the knee extensor muscles. J Appl Physiol 92: 1004–1012, 2002. First published November 2, 2001; 10.1152/japplphysiol.00954.2001.—This study compared the steadiness of submaximal contractions with the knee extensor muscles in young and old adults. Twenty young and twenty old subjects underwent assessment of isometric maximum voluntary contraction (MVC), one-repetition maximum (1-RM) strength, and steadiness during isometric, concentric, and eccentric contractions with the knee extensor muscles. The old adults displayed 33% lower MVC force and a 41% lower 1-RM load. The coefficient of variation for force was significantly greater for the old adults during isometric contractions at 2, 5, and 10% of MVC but not at 50% MVC. The decline in steadiness at low forces experienced by the men was marginally greater than that experienced by the women. The steadiness of concentric and eccentric contractions was similar in young and old adults at 5, 10, and 50% of 1-RM load. Old subjects exhibited greater coactivation of an antagonist muscle compared with young subjects during the submaximal isometric and anisometric contractions. These results indicate that, whereas the ability to exert steady submaximal forces with the knee extensor muscles was reduced in old adults, fluctuations in knee joint angle during slow movements were similar for young and old adults.

aging; steadiness; motor control; muscle strength

The decline in motor performance observed in older adults is usually characterized as a decrease in muscle strength or as a reduction in the maximum power that a muscle can produce (1, 8, 12, 20, 27, 31, 32). To assess other adaptations of the aging neuromuscular system, some investigators have examined the ability of older adults to control muscle force during submaximal contractions. For example, older adults display reduced manipulative capabilities, utilize different strategies when stepping down, and improve balance after training with slow movements (7, 17, 21, 38).

One way to quantify the ability of older adults to control muscle force is to determine the steadiness of submaximal contractions during standardized tasks. This involves measuring the fluctuations in force during isometric contractions and the variations in position, acceleration, or force during anisometric contractions (4, 14, 15, 18, 23, 33, 34). A common finding of these studies is that older adults exhibit greater relative force fluctuations during isometric contractions and more variability in position and acceleration during anisometric contractions. These results indicate that older adults exhibit a reduced ability to exert a precise force during submaximal isometric contractions and use a more variable trajectory during movements.

One feature of these findings that deserves attention is the apparent differences between muscles. For example, old adults are less steady than young adults during both isometric and anisometric contractions with a hand muscle (4, 14, 23, 34), whereas with the elbow flexor muscles the old adults are less steady than young adults during anisometric contractions but not isometric contractions (15). One possible explanation for this difference is that the factors underlying the decline in steadiness with age differ for actions controlled by a single muscle compared with multiple muscles. Our laboratory has found that the altered discharge characteristics of motor units in a hand muscle can contribute to differences in steadiness during isometric contractions (23, 35). Because the relative contribution of single motor units to net muscle force declines as the number of active motor units increases (13), however, it is unlikely that differences in the steadiness of limb muscles are attributable to the behavior of single motor units. Rather, our laboratory found that the impaired steadiness in old adults during anisometric contractions of the elbow flexor muscles was associated with an altered distribution of electromyographic (EMG) activity among the synergist muscles (15). The purpose of this study was to compare the steadiness and EMG activity of young and old adults while they were performing submaximal isometric and anisometric contractions with the knee extensor muscles. Because the four knee extensors insert into a common tendon and are often activated in parallel (28–30), in contrast with the elbow flexor muscles (3, 15), we expected to find no difference in the steadiness of knee extensor muscle contractions between young
and old adults. A preliminary version of these results has been reported in abstract form (36).

METHODS

Twenty young (22.1 ± 2.2 yr, range 19–26 yr) and 20 old (71.5 ± 4.3 yr, range 65–79 yr) subjects volunteered to participate in two experimental sessions. The old subjects underwent a physician-supervised maximal treadmill test to screen for the presence of overt cardiovascular disease. Subjects reported no neurological disease and were free of medications known to influence the assessment of neuromuscular function. Those individuals recruited for the study reported no more than moderate levels of physical activity, defined as <3 h/wk of exercise at a low-to-moderate intensity, and no strength training for at least 1 yr. Subjects provided written, informed consent before participation in the study. The Human Research Committee at the University of Colorado at Boulder approved the procedures used in this study.

Knee Extension Device

The weight-stack machine (Icarian) used for the experiments was modified to enable the measurement of force and position during the various tasks. The subjects were seated in a slightly reclined position on the device with the hip joint at about a right angle and the knee joint at ~1.40 rad (80°) when the muscles were relaxed (straight leg = 3.14 rad). The pelvis and thighs were firmly stabilized with nylon straps, and subjects grasped fixed handgrips at midthigh level during all experimental tasks. The force exerted by the knee extensor muscles during isometric contractions was measured with load cells (0.0075 V/N or 0.048 V/N; Siege-Lebow) that connected each lower leg to the rotating lever of the machine. Force was not measured during the anisometric contractions. The subject was positioned so that the center of rotation of the lever was aligned with the knee joint. A potentiometer (±5% linearity, Bourns) was fixed on the lever at the axis of rotation to measure angular displacement about the knee joint. The rotating lever was connected by a pulley-and-cable system to the weight stack. Movement of the weight stack was prevented for isometric contractions; knee angle was 1.66 rad (95°) for all isometric contractions. The force and angle measurements were displayed on an oscilloscope for subject feedback, digitized at 200 Hz, and stored on computer disk by using Spike2 software (Cambridge Electronic Design, Cambridge, UK).

EMG

The EMGs of the vastus lateralis, vastus medialis, rectus femoris, and biceps femoris muscles were measured during all experimental tasks. A pair of silver-silver chloride electrodes with adhesive disks (8-mm diameter; Beckman) was placed 20 mm apart over the muscle belly, fastened to the skin with tape, and secured with a wide elastic bandage. A reference electrode for each pair of electrodes was placed over the patella. EMG signals were amplified 500–2,000 times, digitized at 1 kHz, and stored on computer. The EMG signals were subsequently filtered (20–500 Hz) by using a finite impulse response filter (Spike 2 software, Cambridge Electronic Design).

The EMG was quantified by determining the average rectified signal (AEMG) for selected intervals. For the MVC and one-repetition maximum (1 RM) strength tasks, the peak AEMG was determined for a 0.5-s interval when the AEMG was maximal. For the steadiness tasks, the AEMG was determined for a 1-s period in the middle of the isometric contraction and for a 0.5-s interval in the middle of the concentric and eccentric contractions. In addition, the pattern of muscle activity during the anisometric contractions was displayed as the AEMG for consecutive 80-ms intervals over the course of the 8-s contraction.

Experimental Protocol

The first session involved isometric contractions, whereas the second session comprised anisometric contractions. In each session, the strength of the individual and the steadiness of submaximal contractions were assessed. Strength was measured with the MVC task for isometric contractions and with the 1-RM task for anisometric contractions. Steadiness was quantified during submaximal isometric and anisometric contractions that were performed at intensities relative to the strength of the knee extensor muscles. Testing for young and old subjects was conducted in an identical manner. The two sessions were separated by 1–7 days.

MVC task. The purpose of this task was to determine the maximum force that the knee extensor muscles could exert during a voluntary isometric contraction performed on the knee extension device. After familiarization with the protocol and a practice trial at a submaximal intensity, subjects were asked to slowly increase the force exerted by the knee extensor muscles to a maximal level and push as forcefully as possible for ~3 s. Subjects were given strong verbal encouragement during this task. A minimum of three trials was performed, with at least a 1-min rest between trials. If we did not obtain MVC forces within 3% of each other, a fourth trial was performed. Both unilateral and bilateral MVCs were measured. Bilateral trials were performed first, followed by unilateral trials for the left and right legs. The maximal force measured during any trial was taken as the MVC force. The peak AEMG, which was used to normalize the activity during submaximal contractions, was determined from the trial in which the maximal AEMG was identified.

To assess the maximum AEMG in the antagonist muscle, subjects performed maximal contractions with the knee flexor muscles. For this task, the position of the load cell on the left leg was reversed and subjects were instructed to pull back as hard as possible with the same timing requirements as those used for the knee extensor muscles. The position of the leg was the same for the MVCs performed with the extensor and flexor muscles. Subjects performed three to four trials, and the peak AEMG for the biceps femoris muscle was determined.

1-RM task. The purpose of this task was to determine the maximum inertial load that the knee extensor muscles could lift over a 0.96-rad range of motion. The task, which began from an initial knee angle of 1.66 rad, required subjects to lift the load at a moderate speed until the limit of the range of motion was achieved (2.62 rad). The target terminal angle and the actual angular displacement of the knee joint were displayed on the oscilloscope, which enabled an investigator to determine whether the desired range of motion was achieved. Subjects were instructed to control the speed of contraction so that terminal knee extension was not assisted significantly by the inertia of the moving load. Identification of the 1-RM load began with a moderate load and increased progressively up to the subject’s maximum, with at least a 1-min rest between trials. Subjects were given strong verbal encouragement during each attempt. When a load was attempted that could not be lifted through the specified range of motion, the last successfully lifted load was recorded as the 1-RM load. Subjects required 8–10 trials to determine the 1-RM load, with only 3–4 trials at near-maximal loads.
Isometric steadiness task. The purpose of this task was to assess the ability of the subject to exert a constant force during submaximal contractions (Fig. 1, A and B). The task involved exerting a submaximal force with the knee extensor muscles for 10–12 s to match the target force displayed on the oscilloscope, which was located 1 m in front of the subject. Subjects performed these submaximal isometric contractions with the left leg at target forces of 2, 5, 10, and 50% of MVC force. For logistical reasons, the 50% trials were performed first by using a less-sensitive load cell (0.0075 V/N), after which the 2, 5, and 10% trials were performed in random order by using the sensitive load cell (0.048 V/N). One practice trial was performed at each force level, followed by two trials that were recorded for subsequent analysis. The gain of the display on the oscilloscope was adjusted so that the location of the target force was similar across forces (9).

Anisometric steadiness task. The purpose of this task was to assess the ability of the subject to lift and lower submaximal loads as steadily as possible (Fig. 1C). The task involved the subject matching the angular displacement about the knee joint to a triangular template that was displayed on the oscilloscope. Subjects were instructed to follow the template as closely and steadily as possible. The template filled the vertical display on the screen and required subjects to lift the load in 4 s and lower it in 4 s. The load was lifted with a concentric contraction and lowered with an eccentric contraction. The average velocity for each contraction was 0.24 rad/s (0.96 rad in 4 s). The submaximal loads were 5, 10, and 50% of the 1-RM load. The trials with the 50% load were performed first, followed by the trials with the 5 and 10% loads in random order. Two practice trials were performed before the two experimental trials, which were recorded for subsequent analysis.

Data Analysis

The data were collected on-line by using isolated bioamplifiers (EMG signal), transducer couplers (force, position) (S-series, Coulbourn), and an analog-to-digital processor (1401 plus, Cambridge Electronic Design). Analysis was performed off-line using Spike2 (Cambridge Electronic Design).

Dependent variables. The dependent variables for the strength tasks were maximum force (N) and the peak AEMG (mV) for the MVC task and the maximum load (kg) and the peak AEMG (mV) for the 1-RM task. For the isometric steadiness task, the mean, standard deviation, and coefficient of variation for force were determined for an 8-s epoch that was selected from the middle of the contraction when the force fluctuated around the target force. The AEMG was calculated during 1 s in the middle of the 8-s interval. Because the relation between target force and quantity of AEMG was linear and similar for young and old subjects, the AEMG recorded during submaximal contractions was expressed as a percentage of the maximum AEMG. For the anisometric steadiness task, the angular displacement data were detrended (24) for each contraction and the standard deviation of position was determined for the middle 1 s of the concentric and eccentric contractions.

Statistical analysis. A three-way, repeated-measures ANOVA (between factors = age group, sex; within factors = load or force) was used to compare the dependent variables between age and sex groups (Statview version 4.0). Tukey’s post hoc comparisons were used, where appropriate, to examine specific differences. When multiple comparisons were used, the Bonferroni correction was employed within a family of comparisons. Data in tables are expressed as means ± SD, whereas data in figures are expressed as means ± SE.

RESULTS

The old (71.5 ± 4.3 yr, n = 20) and young (22.1 ± 2.2 yr, n = 20) subjects were of similar height (Table 1), but the old group had a greater body mass than the young group (70.8 ± 13.4 vs. 64.6 ± 11.8 kg; P = 0.01). The men were significantly taller and heavier than the women (Table 1).

Muscle Strength

The MVC force of the left leg for the old subjects was 33% less than that for the young subjects (Table 1).
Steadiness values during isometric and anisometric contractions

Table 2.

<table>
<thead>
<tr>
<th></th>
<th>Young Men</th>
<th>Young Women</th>
<th>Old Men</th>
<th>Old Women</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Age, yr</td>
<td>Height, cm</td>
<td>Body Mass, kg</td>
</tr>
<tr>
<td>Old subjects</td>
<td>20</td>
<td>71.5 ± 4.3</td>
<td>167 ± 11.3</td>
<td>70.8 ± 13.4*</td>
</tr>
<tr>
<td>Men</td>
<td>10</td>
<td>70.8 ± 3.7</td>
<td>174 ± 8.7†</td>
<td>81.4 ± 9.9†</td>
</tr>
<tr>
<td>Women</td>
<td>10</td>
<td>72.2 ± 4.9</td>
<td>160 ± 8.4</td>
<td>60.2 ± 5.8</td>
</tr>
<tr>
<td>Young subjects</td>
<td>20</td>
<td>22.1 ± 2.2</td>
<td>172 ± 10.7</td>
<td>64.6 ± 11.8</td>
</tr>
<tr>
<td>Men</td>
<td>10</td>
<td>22.4 ± 2.0</td>
<td>180 ± 7.8†</td>
<td>74.3 ± 8.2†</td>
</tr>
<tr>
<td>Women</td>
<td>10</td>
<td>21.7 ± 2.4</td>
<td>164 ± 6.7</td>
<td>54.9 ± 4.3</td>
</tr>
</tbody>
</table>

Values are group means ± SD; n, no. of subjects. MVC, left leg force during a unilateral isometric maximum voluntary contraction; 1-RM load, maximum load lifted with the left leg; MVC AEMG, maximal average rectified electromyogram recorded during the left leg MVC task; 1-RM AEMG, maximum AEMG recorded during the left leg 1-RM task. *P < 0.05 compared with young subjects. †P < 0.05 compared with women.

Within each sex, the age differences were similar, with a 35% decline for the old men and a 33% decrease for the old women. The reductions in anisometric strength were not significantly different from those for MVC force (P > 0.05), with a 42% decrease in 1-RM load for the old subjects compared with the young subjects (Table 1). The declines were 41% for the old men and 43% for the old women. The maximum AEMG during both the MVC and the 1-RM tasks was lower (P < 0.05) in old subjects compared with young subjects and in women compared with men (Table 1).

Isometric Steadiness

For the submaximal isometric contractions, the assessment of steadiness was performed on the average of the two trials and the single trial with the lowest standard deviation of force. Because the results did not differ significantly between these two conditions, only the single-trial data are reported here.

The standard deviation of force increased with target force for both young and old subjects (Table 2, Fig. 2A). The standard deviation was significantly greater for the young subjects at 5, 10, and 50% MVC but similar for the two groups of subjects at 2% MVC. However, the coefficient of variation for force, which normalized the standard deviation to the mean force, was greater for old subjects at 2, 5, and 10% MVC (Fig. 2B). The increase in the coefficient of variation for force with age tended to be greater (range of P values: 0.06–0.08) for the men compared with the women at 2, 5, and 10% MVC (Fig. 3).

Muscle activity was measured in three agonist muscles: vastus lateralis, vastus medialis, and rectus femoris. The results of the statistical analysis were the same for all muscles; therefore, only values for the vastus lateralis are presented. Although the maximal absolute AEMG differed between young and old adults (Table 1), there was no difference due to age or sex in the quantity of EMG during the submaximal contractions when it was normalized to the maximal AEMG (Table 3). For all subjects, vastus lateralis AEMG was 3.12 ± 2.12, 5.98 ± 4.9, 10.3 ± 2.0, and 43.8 ± 13% of maximum AEMG for the 2, 5, 10, and 50% MVC forces, respectively. In contrast, the normalized AEMG for the biceps femoris muscle was greater (P < 0.05) for the old subjects at each submaximal target force. The difference in the amount of biceps femoris AEMG between the old and young subjects was 1.4, 4.6, 3.8, and 8.3% of maximum AEMG at the 2, 5, 10, and 50% MVC forces, respectively.

Table 2. Steadiness values during isometric and anisometric contractions

<table>
<thead>
<tr>
<th></th>
<th>Young SD</th>
<th>Young CV</th>
<th>Old SD</th>
<th>Old CV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Men</td>
<td>Women</td>
<td>Men</td>
<td>Women</td>
</tr>
<tr>
<td>Isometric</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2% MVC</td>
<td>0.336 ± 0.13†</td>
<td>2.30 ± 0.56*</td>
<td>0.202 ± 0.05</td>
<td>2.45 ± 0.56</td>
</tr>
<tr>
<td>5% MVC</td>
<td>0.692 ± 0.19†</td>
<td>2.12 ± 0.35*</td>
<td>0.484 ± 0.27*</td>
<td>2.27 ± 0.57</td>
</tr>
<tr>
<td>10% MVC</td>
<td>1.360 ± 0.35*†</td>
<td>2.04 ± 0.23*</td>
<td>0.789 ± 0.31*</td>
<td>2.20 ± 0.51</td>
</tr>
<tr>
<td>50% MVC</td>
<td>9.925 ± 3.69*†</td>
<td>2.96 ± 0.76*</td>
<td>4.991 ± 1.14*</td>
<td>2.62 ± 0.68</td>
</tr>
<tr>
<td>Concentric</td>
<td></td>
<td></td>
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<tr>
<td>5% 1 RM</td>
<td>0.297 ± 0.03</td>
<td>0.286 ± 0.03</td>
<td>0.271 ± 0.05</td>
<td>0.252 ± 0.08</td>
</tr>
<tr>
<td>10% 1 RM</td>
<td>0.269 ± 0.02</td>
<td>0.258 ± 0.02</td>
<td>0.264 ± 0.04</td>
<td>0.253 ± 0.10</td>
</tr>
<tr>
<td>50% 1 RM</td>
<td>0.253 ± 0.04</td>
<td>0.237 ± 0.04</td>
<td>0.224 ± 0.06</td>
<td>0.280 ± 0.10</td>
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<tr>
<td>Eccentric</td>
<td></td>
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<tr>
<td>5% 1 RM</td>
<td>0.244 ± 0.03</td>
<td>0.232 ± 0.04*</td>
<td>0.223 ± 0.06†</td>
<td>0.189 ± 0.04</td>
</tr>
<tr>
<td>10% 1 RM</td>
<td>0.269 ± 0.02*</td>
<td>0.237 ± 0.03</td>
<td>0.200 ± 0.05†</td>
<td>0.207 ± 0.05</td>
</tr>
<tr>
<td>50% 1 RM</td>
<td>0.250 ± 0.03</td>
<td>0.232 ± 0.03</td>
<td>0.216 ± 0.04†</td>
<td>0.203 ± 0.07</td>
</tr>
</tbody>
</table>

Values are group means ± SD. Standard deviation (SD), standard deviation of force (isometric task) or detrended position signal (anisometric task); coefficient of variation (CV), standard deviation divided by mean force (isometric task). *P < 0.05 for young compared with old. †P < 0.05 for men compared with women. ‡P < 0.05 for 50% 1 RM compared with 5% 1 RM.
Steadiness during the concentric and eccentric contractions was based on the standard deviation of knee angle during the middl e1so feach contraction (see METHODS). The standard deviation of position was less during the concentric contraction with the 50% load compared with the 5% load \((P < 0.05)\); there were no other significant differences in standard deviation across loads for concentric or eccentric contractions (Table 2).

The standard deviation was not different between old and young subjects during the concentric contractions with any load (Table 2). The effect was similar for the eccentric contractions, with the standard deviations only significantly greater for young women compared with old women at the 5% load and greater for young men compared with old men at the 10% load (Table 2).

To examine the pattern of EMG activity during the anisometric contractions, the AEMG of the vastus lateralis was determined for 80-ms intervals across each trial and the intervals were averaged across subjects (Fig. 4). The AEMG increased more-or-less linearly during the concentric contractions with light loads (5% 1 RM in Fig. 4) and decreased during the eccentric contraction. This pattern was evident for both the agonist (vastus medialis, vastus lateralis, and rectus femoris) and antagonist (biceps femoris) muscles. With the heaviest load (50% 1 RM in Fig. 4), however, the change in AEMG was not monotonic during either the concentric or eccentric contractions. Nonetheless, neither the pattern of AEMG nor the average value for the agonists during the middle of the trial was different between young and old subjects for the three loads (Table 3). The average AEMG for biceps femoris, however, was greater for the old adults at most loads (Table 3).

There was a main effect of contraction type in that the normalized AEMG of the agonist muscles was less \((P < 0.05)\) during eccentric contractions compared with concentric contractions (Fig. 4). There were no significant differences between age groups or sex for this relation. Furthermore, AEMG for the antagonist muscle was less during eccentric contractions compared with concentric contractions with the 50% 1-RM load but not with the 5 or 10% loads (Fig. 4). Old and young subjects exhibited a similar difference in antagonist AEMG between eccentric and concentric contractions (Table 3).

DISCUSSION

The main finding was that old adults exhibited impaired steadiness during low-force isometric contractions but not during slow anisometric contractions with the knee extensor muscles. Old subjects also used greater coactivation of an antagonist muscle during both types of contractions. For low-force isometric contractions, there was a trend toward a greater difference...
Table 3. Vastus lateralis and biceps femoris AEMG for the forces and loads used during isometric and anisometric contractions

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Young Isometric</th>
<th>Young Concentric</th>
<th>Young Eccentric</th>
<th>Old Isometric</th>
<th>Old Concentric</th>
<th>Old Eccentric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vastus lateralis</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2% MVC</td>
<td>2.45 ± 0.90</td>
<td></td>
<td></td>
<td>3.96 ± 2.68</td>
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</tr>
<tr>
<td>5% MVC</td>
<td>5.21 ± 2.68</td>
<td>7.13 ± 3.00</td>
<td>5.15 ± 2.12</td>
<td>6.75 ± 3.61</td>
<td>11.6 ± 5.31</td>
<td>7.82 ± 3.71</td>
</tr>
<tr>
<td>10% MVC</td>
<td>8.80 ± 3.45</td>
<td>8.38 ± 4.08</td>
<td>7.12 ± 4.36</td>
<td>11.8 ± 4.81</td>
<td>13.3 ± 5.57</td>
<td>9.49 ± 4.05</td>
</tr>
<tr>
<td>50% MVC</td>
<td>39.1 ± 8.87</td>
<td>32.8 ± 8.49</td>
<td>23.9 ± 5.73</td>
<td>48.5 ± 15.4</td>
<td>38.1 ± 12.5</td>
<td>26.8 ± 9.65</td>
</tr>
<tr>
<td>Biceps femoris</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>2% MVC</td>
<td>1.13 ± 0.47*</td>
<td>3.04 ± 2.76*</td>
<td>1.97 ± 1.48</td>
<td>6.40 ± 6.45</td>
<td>6.92 ± 4.20</td>
<td>5.79 ± 4.42</td>
</tr>
<tr>
<td>5% MVC</td>
<td>1.82 ± 1.12*</td>
<td>3.74 ± 2.93</td>
<td>2.42 ± 2.15</td>
<td>6.88 ± 5.07</td>
<td>7.08 ± 4.17</td>
<td>6.15 ± 4.81</td>
</tr>
<tr>
<td>10% MVC</td>
<td>3.08 ± 2.22*</td>
<td>10.9 ± 6.46*</td>
<td>7.94 ± 4.53*</td>
<td>21.0 ± 14.6</td>
<td>16.3 ± 10.3</td>
<td>12.8 ± 8.68</td>
</tr>
<tr>
<td>50% MVC</td>
<td>12.7 ± 7.46*</td>
<td>10.9 ± 6.46*</td>
<td>7.94 ± 4.53*</td>
<td>21.0 ± 14.6</td>
<td>16.3 ± 10.3</td>
<td>12.8 ± 8.68</td>
</tr>
</tbody>
</table>

Values are group means ± SD. AEMG was calculated for 1 s in the middle of the isometric task, or for 0.5 s in the middle of the concentric or eccentric phase of the anisometric task, and expressed as a percentage of the maximum isometric AEMG. *P < 0.05 for young compared with old. Statistical results for the vastus lateralis were similar to the other agonist muscles (vastus medialis, rectus femoris) tested.

in steadiness between young and old men compared with the difference between young and old women.

The old subjects were weaker, as indicated by a 33% lower MVC force and 41% lower 1-RM load compared with young subjects. These decreases are consistent with previous reports on the decline in strength of the knee extensor muscles of older adults (11, 16, 22, 25). For example, Klitgaard et al. (22) reported 44% lower isometric MVC values in the knee extensor muscles of old compared with young adults. Similarly, the 1-RM load of the knee extensor muscles has been reported to be 17% less in old adults compared with young adults (26). Thus the subjects included in our study exhibited a decline in strength that is representative of normal aging.

Isometric Steadiness and Aging

The steadiness of isometric contractions performed at low forces with the knee extensor muscles was reduced in old subjects. Although this result appears to contrast with those reported in three other studies on the knee extensor muscles, there are critical methodological differences that prevent direct comparisons with the present study. First, Hortobágyi et al. (18) found no differences between young and old adults in force control during isometric contractions performed with the knee extensor muscles. Hortobágyi et al., however, calculated the standard deviation and coefficient of variation for force during an entire 5 s force-matching task, which included the rise-to-target and settling-in phases of the task. In contrast, our analysis focused on the plateau portion of the ramp-and-hold task (see Fig. 1). Additionally, Hortobágyi et al. used the same absolute target force of 25 N for both age groups, which corresponded to 6% MVC force for young subjects and 12% MVC force for old subjects. Thus the steadiness of muscle contractions was not addressed in a manner comparable to our previous work in the upper extremity (14, 15, 23).

Second, Schiffman and Luchies (33) observed no differences between young and old adults in the variability of force during isometric contractions with the knee extensor muscles. The protocol used by Schiffman and Luchies, however, required subjects to maintain the exerted torque within a range of 6.1 N·m relative to the target rather than exert a constant torque. Because of differences in MVC torque between the subjects, the target window (6.1 N·m) corresponded to 3.7% MVC torque for the young subjects and 5.9% MVC torque for the old subjects at a target of 20% MVC torque. Thus the older subjects were given a less strict criterion, and
there was no difference between the two groups of subjects in the standard deviation of the torque during this task.

Third, Christou and Carlton (6) observed no differences between young and old adults in the coefficient of variation for force during isometric contractions of the knee extensor muscles performed on an isokinetic dynamometer across target forces that ranged from 5 to 90% MVC. Differences between the two studies that may have contributed to the contrary results include the physical status of the subjects and the type of visual feedback provided during the steadiness task. Christou and Carlton studied subjects who performed high levels of daily physical activity and were much stronger than those in our study, which may contribute to differences in steadiness (2, 19). Furthermore, Christou and Carlton measured steadiness when the subjects had no visual feedback, the quality of which has a direct effect on differences in steadiness between young and old adults (9). Therefore, our results represent novel findings on impaired steadiness during low-force isometric contractions with the knee extensor muscles of old adults and extend our observations on the first dorsal interosseus and elbow flexor muscles (4, 14, 15, 23).

Anisometric Contractions

The young and old adults in this study exhibited similar fluctuations in knee angle during lifting and lowering of loads ranging from 5 to 50% of maximum. These results contrast those on the first dorsal interosseus and elbow flexor muscles, as indicated by greater fluctuations in position (23) or acceleration normalized to the load lifted (4, 15, 24). Although significant methodological differences prevent a direct comparison between these studies, our results on the knee extensor muscles also contrast those of Hortobágyi et al. (18), who observed a greater standard deviation of force in old adults during concentric and eccentric contractions performed with the knee extensor muscles on an isokinetic dynamometer. Our results agree with those of Schiffman and Luchies (33), however, who found no differences in force variability between young and old adults during concentric contractions performed on an isokinetic dynamometer.

As stated previously, the observed differences in findings between these studies are likely attributable to the details of the tasks performed and the methods used to quantify steadiness (18, 33). For example, it is possible that assessment of steadiness during anisometric contractions based on a signal from a potentiometer is not sensitive enough to detect differences in the steadiness of the force exerted by the muscles during a movement. This might be due to greater damping of the fluctuations in muscle force by the greater mass of connective tissue, tendon, and experimental apparatus present in this model. Indeed, analysis of unpublished data from our laboratory indicates that the standard deviation of the detrended position signal during concentric and eccentric contractions performed with the knee extensor muscles is not positively related to the standard deviation of acceleration during the same contractions. This suggests that the position signal is not as sensitive as the acceleration signal, which has previously been used to examine differences in the steadiness of anisometric contractions between old and young adults (4, 15). An alternative possibility is that there is no difference in the steadiness of anisometric contractions performed with the knee extensor muscles between these two samples of young and old adults.

The neural mechanisms that have the potential to explain the reduced steadiness of old adults include alterations in the characteristics or discharge behavior of motor units (5), alternating bursts of activity in agonist and antagonist muscles (37), and alterations in the ability to coordinate multiple agonist muscles (15). Individual motor unit activity was not measured in this study, but the surface EMG data indicated that the distribution of activation across the knee extensor agonist muscles was not substantially different between the young and old subjects during isometric and anisometric contractions. Furthermore, there were no differences between young and old subjects in the pattern of muscle activity during anisometric contractions (Fig. 4). As we expected (see introduction), a similar pattern of parallel activation of the agonist muscles by the young and old subjects was associated with similar levels of steadiness in the position signal. Although the magnitude of antagonist coactivation during isometric and anisometric contractions was greater in old subjects at all target levels (Table 3), the pattern of activity was not different. Qualitative inspection of the antagonist EMG records, however, revealed no bursting pattern of EMG that would serve to explain the enhanced fluctuations in isometric force.

Differences Between Muscle Groups

Several features of the steadiness of submaximal muscle contractions performed by older adults are different between the first dorsal interosseus, elbow flexor, and knee extensor muscles. One feature is the magnitude of the effect of age on steadiness. For example, we found that the coefficient of variation for force during isometric contractions of the knee extensor muscles at 2, 5, and 10% MVC was 41, 23, and 14% greater in old compared with young subjects but not different at 50% MVC. These differences are smaller than those observed in the first dorsal interosseous muscle by Galganski et al. (14), who reported a 67% greater coefficient of variation for force at 5% MVC and a 35% greater coefficient of variation for force at 50% MVC in old compared with young subjects. Furthermore, Laidlaw et al. (23) found even larger age-related differences in the coefficient of variation for force during isometric contractions with the first dorsal interosseus muscle of 132, 158, and 123% at 2.5, 5, and 10% of MVC, respectively. The results obtained during isometric contractions with the elbow flexor muscles, however, differ from those for the first dorsal interosseous...
and knee extensor muscles. Graves et al. (15) found no difference in the coefficient of variation for force between young and old subjects during isometric contractions performed with the elbow flexor muscles at levels ranging from 5 to 65% MVC. It appears, therefore, that the effect of age on the steadiness of isometric contractions is greater in the first dorsal interosseus muscle compared with the knee extensor muscles, and it is certainly greater compared with the elbow flexor muscles.

For the steadiness of isometric contractions, there are clear differences in the effect of age on the first dorsal interosseus and knee extensor muscles during concentric and eccentric contractions. For example, Burnett et al. (4) found in old adults that the normalized standard deviation of acceleration during concentric contractions was 91% greater at 5% 1 RM and 38% greater at 50% 1 RM in the first dorsal interosseus compared with our finding of no differences in the knee extensor muscles. In addition, the effect of age on the steadiness of eccentric contractions performed with the first dorsal interosseus were increases of 174 and 178% at 5 and 50% 1 RM compared with no differences for the knee extensor muscles. Moreover, the 76% reduction in the steadiness of eccentric contractions (pooled across loads) observed in the elbow flexor muscles of old adults is greater than the 33% reduction observed in concentric contractions (15). These differences due to age in the elbow flexor muscles for concentric contractions are not substantially different from those observed in the first dorsal interosseus, but the differences for eccentric contractions are less than those observed in the first dorsal interosseus. In contrast with the knee extensor muscles, the reduced steadiness exhibited by old adults when performing isometric contractions with the elbow flexor muscles was associated with marked differences in the distribution of activity among the agonist muscles. Taken together, these findings suggest that the effect of age on steadiness is dependent on the muscle group and type of contraction.

Another feature of steadiness that differs between the muscle groups is the relative steadiness of concentric compared with eccentric contractions. Previous investigations have shown that the steadiness of eccentric contractions is reduced compared with shortening contractions for both the first dorsal interosseus and the elbow flexor muscles of old adults (15, 24). This difference is probably attributable to unique neural strategies used during eccentric contractions, such as altered muscle activation and motor unit discharge characteristics (10). The present data, however, indicate no significant difference in steadiness (fluctuations in position) between slow concentric and eccentric contractions for the knee extensor muscles.

In summary, the steadiness of old adults was reduced compared with young adults during isometric contractions, but not during concentric and eccentric contractions, with the knee extensor muscles. The decline in steadiness was not associated with differences in the magnitude or pattern of agonist muscle activity as recorded with surface EMG electrodes. Although the old subjects exhibited greater coactivation of an antagonist muscle, there were no differences in the pattern of antagonist activity between young and old adults. Differences in the steadiness of isometric contractions between young and old adults are greater for the first dorsal interosseus muscle compared with the knee extensor and elbow flexor muscles. Furthermore, the steadiness of eccentric contractions appears to decrease more with age in the first dorsal interosseus muscle compared with the elbow flexor and knee extensor muscles.

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