Strength training reduces force fluctuations during anisometric contractions of the quadriceps femoris muscles in old adults

Brian L. Tracy, William C. Byrnes, and Roger M. Enoka
Department of Integrative Physiology, University of Colorado, Boulder, Colorado 80309-0354

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Tracy, Brian L., William C. Byrnes, and Roger M. Enoka. Strength training reduces force fluctuations during anisometric contractions of the quadriceps femoris muscles in old adults. J Appl Physiol 96: 1530–1540, 2004. First published October 17, 2003; 10.1152/japplphysiol.00861.2003.—The greater fluctuations in motor output that are often exhibited by old adults can be reduced with strength training. The purpose of the study was to determine the effect of strength and steadiness training by old adults on fluctuations in force and position during voluntary contractions with the quadriceps femoris muscle. Healthy old adults (65–80 yr) completed 16 wk of heavy-load (80% of maximum, n = 11) strength training, heavy-load steadiness training (n = 6), or no training (n = 9). Steadiness training required subjects to match the angular displacement about the knee joint to a constant-velocity template. The Heavy-Load group experienced a 5.5% increase in muscle volume, a 25% increase in maximal voluntary contraction force, and a 26% increase in the one-repetition maximum (1-RM) load. The Heavy-Load Steady group experienced increases of 11.5, 31, and 36%, respectively. The maximal electromyogram signal of quadriceps femoris increased by 51% in the two training groups. The coefficient of variation (CV) for force during submaximal isometric contractions did not change with training for any group. Although both training groups also experienced a reduction in CV for force during anisometric contractions with a 50% 1-RM load, the standard deviation of position did not change with time for any group. The Heavy-Load Steady group also experienced a reduction in CV for force during the training contractions performed with the 80% 1-RM load. Thus strength training reduced the force fluctuations of the quadriceps femoris muscles during anisometric contractions but not during isometric contractions.

METHODS
Twenty-six old adults (77.7 ± 4.8 yr, range 65–79 yr) underwent a physician-supervised treadmill test to screen for the presence of overt cardiovascular disease. Subjects reported and exhibited no neurological disease, were free of medications known to influence the dependent measures, and reported <3 h/wk of low- to moderate-intensity endurance exercise with no strength training for at least the previous year. Subjects were oriented to the procedures and provided written, informed consent before participation in the study. The Human Research Committee at the University of Colorado in Boulder approved the procedures.

Experimental Design
Subjects randomly drew assignments to one of three experimental groups: 1) Heavy-Load subjects who performed strength training with heavy loads, 2) Heavy-Load Steady subjects who performed strength training with heavy loads, and 3) Normal subjects who performed no strength training. The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.
training with heavy loads while performing steady contractions, and 3) Control subjects who performed no training. Subjects were tested at 0, 2, 8, and 16 wk. Testing consisted of two sessions that were separated by 1 day. The first session comprised determination of the isometric maximal voluntary contraction (MVC) and the measurement of force fluctuations during isometric contractions. The second session involved identification of the one-repetition maximum (1-RM) load, the measurement of fluctuations during anisometric contractions, and the performance of physical function tests. Subjects underwent magnetic resonance imaging before and after training.

Experimental Setup

The weight-stack machine (Icarian, Sun Valley, CA) used for training and 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 (straight leg = 3.14 rad). The pelvis and thighs were firmly stabilized with nylon straps, and subjects grasped handgrips at midheight level during all experimental tasks. The force exerted by the quadriceps femoris muscles during anisometric contractions was measured with load cells (0.0075 or 0.048 V/N; Siebe-Lebow) that connected each lower leg to the weight-stack machine. The subject was positioned so that the knee joint was collinear with the center of rotation of the lever that moved the weight stack. 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 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 use of Spike2 software (Cambridge Electronic Design, Cambridge, UK).

Training Protocol

Subjects assigned to the two training groups participated in 16 wk of training. Subjects performed three sets of 10 repetitions of a knee-extension task three times per week with each leg separately. The task involved lifting and lowering a load with concentric and eccentric contractions of the quadriceps femoris muscles. Heavy-Load and Heavy-Load Steady training involved loads that were 80% of 1-RM load. Training loads were updated weekly on the basis of the previous training studies in our laboratory. The trials at 50% MVC were performed first using a less sensitive load cell (maximum = 1.335 N), after which the 2, 5, and 10% trials were performed in random order using a more sensitive load cell (maximum = 222 N). One practice trial was performed at each force level, followed by two trials that were recorded for analysis. The task was to increase the force exerted by the quadriceps femoris muscles to match a target force displayed as a horizontal line on the oscilloscope. Subjects were instructed to match the target as steadily as possible for 10–12 s. Vertical gain on the oscilloscope was adjusted so that the sensitivity of the force feedback presented to the subject was similar across force levels. The oscilloscope was placed 75 cm in front of the subject. The dependent variables for the isometric contractions were mean force during an 8-s epoch, standard deviation (SD) of the force, coefficient of variation (CV) for force [(SD/mean force) × 100], and average rectified EMG signal (AEMG) during a 1-s period in the middle of the 8-s constant-force epoch (Fig. 1).

1-RM load. Subjects extended the knee joint from 1.66 to 2.62 rad (3.14 rad = straight leg), with the end of the range of motion indicated by a vertical target line on the oscilloscope. For each repetition, subjects extended the joint until the position signal reached the target line. An investigator monitored completion of the task. The assessment began with a moderate load and increased progressively up to the maximum. Subjects were given a 60-s rest between attempts. 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. The maximal load was usually determined within 8–10 trials, with only 2–3 of those trials at near-maximal loads.

Anisometric contractions. After the 1-RM assessment, subjects lifted and lowered loads of 5, 10, or 50% of the 1-RM load with the left leg. The 50% trials were performed first, followed by the 5 and 10% trials in random order. The task involved matching the displacement about the knee joint to a constant-velocity target line on the oscilloscope (Fig. 1A). Subjects were instructed to follow the template as closely and steadily as possible. The template was designed so that the range of motion filled the vertical axis and the concentric (4-s lifting action) and eccentric (4-s lowering action) contractions filled the horizontal axis. Two practice trials were performed before two trials that were recorded for analysis. The analysis involved determining the fluctuations in position around the average movement velocity (Fig. 1). Fluctuations in force were measured during contractions with the 50% 1-RM load. A regression line was fitted through the position or force signal during the concentric or eccentric phase and the slope of the line (constant velocity) was removed from the data. Because the amplitude of the fluctuations in position and force with the observed spectral characteristics are only weakly related to one another, the standard deviation of the detrended position (deg) and force (N) signals were calculated for the entire concentric or eccentric phase.

Experimental Measurements

In addition to the measurement of position and force during the four experimental tasks, assessments were made of muscle activity during the tasks, fluctuations in force during training in the Heavy-Load Steady group, changes in physical function capabilities, and muscle size.

EMG recordings. The EMG of the vastus lateralis, vastus medialis, rectus femoris, and biceps femoris muscles was measured during all experimental tasks. Pairs of silver-silver chloride electrodes with
Because there were no differences in the changes in muscle volume between the groups, the cross-sectional area (cm²) of the quadriceps femoris muscle group was used in the analysis. A composite time was determined for each subject by summing the times taken for the usual gait speed, chair rise, stair ascent, and stair descent tasks.

Magnetic resonance imaging. To document the muscle hypertrophy in response to training, a series of T1-weighted axial sections of both thighs was acquired, ranging from the superior border of the patella to the anterior superior iliac spine, encompassing the entire quadriceps femoris muscle group. Images were acquired with a 256 × 256 pixel matrix and a 48-cm field of view for the first few subjects, and a 512 × 512 pixel matrix and 24-cm field of view was used for the remaining subjects. All of the images were acquired with a relaxation time of 275 ms, echo time of 15 ms, slice width of 10 mm, and a gap between sections of 10 mm. The pixel matrix and field of view were the same before and after training for each subject.

The cross-sectional area (cm²) of the quadriceps femoris muscle group was measured by using NIH Image version 1.61 (National Institutes of Health, http://rsb.info.nih.gov/nih-image/) in axial sections every 4 cm from the knee to the hip (36). Muscle volume (cm³) was estimated by determining the product of the distance between the slices and the summed cross-sectional areas of the sections. The same investigator, blinded to subject identity and the time of measurement, performed measurements before and after training for each subject. Because there were no differences in the changes in muscle volume fluxes during training. The force exerted by the left leg during the second set of training repetitions was recorded during each of the 48 training sessions. The training task for the Heavy-Load Steady group was to lift and lower the training load with concentric and eccentric contractions to match a constant-velocity template; thus the force fluctuated around a slightly increasing mean force during the concentric contractions and a similarly decreasing force during the eccentric contractions (Fig. 1A). After the slope of the force was removed from the force record, the standard deviation and CV for force were measured. This provided a measure of force fluctuations as the training program progressed. Because the Heavy-Load group lifted the training loads at a self-selected velocity, the force during the training contractions did not fluctuate around a mean force and thus was not amenable to measurements of force fluctuations.

Physical function tests. Subjects performed three tests of functional performance capabilities: 1) usual and fastest gait speeds, 2) chair rise, and 3) stair ascent and descent. To evaluate gait speed, subjects performed two timed trials on a 10-m course at their usual walking pace and two trials as fast as they could walk. The two trials for usual gait speed were averaged, whereas the briefer time for the fast walk was used in the analysis. For the chair-rise task, subjects were seated in a straight-backed chair with a seat height of 42 cm above the floor. They were instructed to rise to a fully standing position and sit back down five times as fast as possible with their arms crossed in front of their chest. To examine stair-climbing ability, the subjects were instructed to ascend and descend a flight of stairs (16 steps, 16-cm step height) as rapidly and safely as possible. Ascent and descent were performed separately, with spotting provided by a research assistant. The fastest times for the chair rise and stair climbing were used in the analysis. A composite time was determined for each subject by summing the times taken for the usual gait speed, chair rise, stair ascent, and stair descent tasks.

Fig. 1. Example data from an old adult performing a training contraction (A), an isometric contraction (B), and an anisometric contraction (C). The data for the contraction during training include knee joint angle (top trace) and the force exerted at the ankle because of contraction of the quadriceps femoris muscle (bottom trace). The data for the isometric contraction comprise the interference electromyogram (EMG) for biceps femoris (top trace) and vastus lateralis (middle trace) and the force exerted at the ankle (bottom trace). The data for the anisometric contraction include the 2 interference EMGs (biceps femoris and vastus lateralis) and knee joint angle (bottom trace).
between left and right legs, the values were summed across the left and right legs (cm$^3$).

**Data Analysis**

All data were collected on-line by use of S-series bioamplifiers (EMG signal) and transducer couplers (force, position) (Coulbourn Instruments, Allentown, PA) and an analog-to-digital processor (1401 plus, Cambridge Electronic Design). Analysis was performed offline by use of the Spike2 data analysis system (Cambridge Electronic Design) with custom software.

Repeated-measures ANOVA was used. Where appropriate, the between-subjects factor was training group. The within-subjects factors were time (0, 2, 8, 16 wk), muscle (vastus lateralis, vastus medialis, and rectus femoris), force (2, 5, 10, 50% MVC) or load (5, 10, 50% 1-RM), and contraction type (concentric, eccentric). Specific post hoc comparisons were used to examine differences and interactions between groups as appropriate. The Bonferroni correction was employed for multiple comparisons. The relations between variables were characterized by simple linear regression.

There were missing AEMG data at low target forces and loads because of low signal-to-noise ratios. Thus only subjects who had complete data across time, muscle, target force, load, or contraction type were included in some statistical analyses. The cell means in the tables, however, represent the maximum number of subjects.

**RESULTS**

Age, height, body mass, and body mass index of the subjects did not differ between the groups before training ($P > 0.05$; Table 1).

**Strength Changes**

There were no differences in summed left and right leg MVC forces or 1-RM loads before training between the experimental groups (Table 2). The two training groups (Heavy-Load and Heavy-Load Steady) experienced 25 and 31% increases in MVC force and 26 and 36% increases in 1-RM load after training, respectively, which were significantly greater ($P < 0.05$) than the Control group (Fig. 2, A and B). Strength gains were similar for the two training groups ($P > 0.05$). Relative increases for individual subjects in the two training groups ranged from 4–54% for MVC force and 3–90% for 1-RM load.

Although MVC force was correlated with 1-RM load in the two training groups before training ($r^2 = 0.78, P < 0.0001$), the change in MVC force was not correlated with the change in 1-RM load ($r^2 = 0.1, P = 0.2$). This effect was due to a moderate correlation between the gain in MVC force and the pretraining MVC force ($r^2 = 0.33$, $P = 0.016$), but no correlation between the increase in 1-RM load and the initial 1-RM load ($r^2 = 0.13, P = 0.15$).

MVC force normalized to muscle volume before training was greater in the Control group (0.37 ± 0.037 N/cm$^3$) compared with the Heavy-Load group (0.268 ± 0.41 N/cm$^3$) and the Heavy-Load Steady group (0.294 ± 0.06 N/cm$^3$, $P < 0.05$). Normalized maximal force did not change in the Control group ($P > 0.05$), but it increased similarly for the two training groups (16.3%).

**Muscle Volume**

There were no differences before training in the volume (cm$^3$) of the quadriceps femoris between the three groups for left leg, right leg, or summed left and right legs ($P > 0.05$). Muscle volume increased significantly ($P < 0.05$) for both the Heavy-Load (5.5 ± 3.9%) and Heavy-Load Steady (11.5 ± 2.3%) groups but not the Control group (−1.5 ± 2.6%) (Fig. 2). The increase in muscle volume was significantly greater in the Heavy-Load Steady group compared with the Heavy-Load group ($P < 0.05$ for the group × time interaction). The percent change in muscle volume with training was not related to the value at baseline ($P > 0.05$).

**Fluctuations in Force and Position**

The Heavy-Load Steady group displayed a progressive decline in the CV for force during training contractions with 80% 1-RM loads ($P < 0.05$). The CV for force declined over the 16 wk of training from 3.7 ± 1.1 to 1.7 ± 0.48% during concentric contractions and from 3.2 ± 0.5 to 1.2 ± 0.24% during eccentric contractions (Fig. 3).

Similarly, the training groups (Heavy-Load Steady and Heavy-Load) displayed a decline in the CV for force during experimental concentric (4.12 ± 1.1 to 2.87 ± 1.1%) and eccentric (5.49 ± 1.4 to 3.32 ± 1.0%) contractions with 50%
1-RM loads (Fig. 3). The decline was significant from 0 to 8 wk training with no further decline at 16 wk and was significantly different from the Control group \((P < 0.05)\). The reduction for eccentric contractions was significantly greater than the response for concentric contractions (contraction type-by-time interaction, \(P < 0.05\)).

**Force fluctuations during isometric contractions.** The average values for the SD of force ranged from 0.2 to 5.0 N (Table 2).
Table 3. Standard deviation of force during constant-force isometric contractions

<table>
<thead>
<tr>
<th>Group and Target Force</th>
<th>Week 0</th>
<th>Week 2</th>
<th>Week 8</th>
<th>Week 16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy-Load Steady (n = 6)</td>
<td>2%</td>
<td>0.208±0.131</td>
<td>0.251±0.175</td>
<td>0.201±0.098</td>
</tr>
<tr>
<td></td>
<td>5%</td>
<td>0.367±0.082</td>
<td>0.455±0.185</td>
<td>0.458±0.159</td>
</tr>
<tr>
<td></td>
<td>10%</td>
<td>0.787±0.157</td>
<td>0.901±0.274</td>
<td>0.883±0.295</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>4.36±1.14</td>
<td>4.20±0.998</td>
<td>4.24±1.25</td>
</tr>
<tr>
<td>Heavy-Load (n = 11)</td>
<td>2%</td>
<td>0.246±0.145</td>
<td>0.240±0.119</td>
<td>0.230±0.116</td>
</tr>
<tr>
<td></td>
<td>5%</td>
<td>0.422±0.225</td>
<td>0.457±0.271</td>
<td>0.469±0.224</td>
</tr>
<tr>
<td></td>
<td>10%</td>
<td>0.825±0.420</td>
<td>0.971±0.521</td>
<td>0.987±0.509</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>4.11±2.15</td>
<td>4.69±2.38</td>
<td>4.75±2.21</td>
</tr>
<tr>
<td>Control (n = 9)</td>
<td>2%</td>
<td>0.239±0.110</td>
<td>0.224±0.073</td>
<td>0.235±0.098</td>
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<tr>
<td></td>
<td>5%</td>
<td>0.495±0.186</td>
<td>0.467±0.186</td>
<td>0.428±0.135</td>
</tr>
<tr>
<td></td>
<td>10%</td>
<td>0.857±0.205</td>
<td>0.991±0.232</td>
<td>0.890±0.271</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>4.97±1.44</td>
<td>5.01±1.81</td>
<td>4.51±1.42</td>
</tr>
</tbody>
</table>

Values are means ± SD; n, number of subjects. *P < 0.05 compared with week 0 for the pooled results of the Heavy-Load Steady and Heavy-Load groups.

3) and did not change across time for the Control group (P > 0.05). Because the change in the standard deviation of force was similar for the two training groups, the data were pooled. The standard deviation of force increased significantly with training at the 5 and 10% target forces (P < 0.05) but did not change at the 2 and 50% MVC target forces (Table 3, P > 0.05). Only at the 5% MVC target force, however, was the increase (0.402 ± 0.19 to 0.491 ± 0.23 N) different from the Control group (group by time interaction, P < 0.05). The average CV for force ranged from 2.3 to 3.3% across groups and force levels (Table 4). The CV for force did not change across time (weeks) at any target force level (Table 4). Because the change in the standard deviation of force did not change across time with training (2.51 ± 0.6 to 2.26 ± 0.4%, P = 0.009), this change was not different from the nonsignificant change for the Control group (2.66 ± 0.8 to 2.29 ± 0.5%). There was, however, a distribution of responses around the average change, such that subjects exhibited either an increase or decrease in the CV for force. For the two lowest target forces, there was a significant negative correlation between absolute change in the CV for force and the value before training (Fig. 5). Subjects with a high CV for force before training experienced the greatest reductions in the normalized fluctuations, and vice versa. Changes in the CV for force at each target force were not related to MVC force before training (P > 0.05).

Position fluctuations during isometric contractions. For both concentric and eccentric contractions with all submaximal loads (5, 10, and 50% 1-RM), the standard deviation of the detrended position signal did not change (P > 0.05) across the 16 wk for the Control, Heavy-Load, or Heavy-Load Steady groups (Fig. 6). There was no interaction between the Control group and the Training groups (P > 0.05). The average standard deviation of position ranged from 0.54 ± 0.11 to 0.66 ± 0.046 deg across groups, force levels, and contraction types.

EMG Activity

The maximal AEMG during the MVCSs before training was similar for the three groups of subjects for the vastus lateralis (0.201 ± 0.126 mV), vastus medialis (0.224 ± 0.158 mV), rectus femoris (0.180 ± 0.102 mV), and biceps femoris (0.134 ± 0.069 mV) muscles (P > 0.05). Because the change in maximal AEMG was similar for the two training groups (group × time interaction, P > 0.05) and the four muscles (muscle × time interaction, P > 0.05), the data were averaged across agonist muscles and pooled for the two groups. The subjects in the two training groups experienced a 51.1 ± 46.6% increase in maximal agonist AEMG (P < 0.05), which was greater than that exhibited by the Control group (group by time interaction, P < 0.05). The maximal AEMG for the antagonist muscle (biceps femoris) did not change for either group (P > 0.05).

When normalized to the AEMG recorded during an MVC, the EMG at each target force (2, 5, 10, and 50%) during the
Fig. 4. Normalized fluctuations in force during isometric contractions. Percent changes in the CV for force for Control and training groups during isometric contractions at 2% (A), 5% (B), 10% (C), and 50% (D) MVC target forces are shown. *P < 0.05 compared with week 0. Values are means ± SE.

Fig. 5. Changes in the CV for force relative to the CV for force before training at 2% (A), 5% (B), 10% (C), and 50% (D) MVC target forces. CV for force, coefficient of variation for force during isometric contractions. Individual values are shown for subjects in the Heavy-Load and Heavy-Load Steady groups. The values for 2 clear outliers, which significantly strengthened the associations, have been omitted.
isometric contractions was similar for the three groups of subjects and did not change across the 16 wk ($P > 0.05$). For example, the normalized EMG for contractions at 2% MVC was $3.69 \pm 2.5\%$ before and $4.42 \pm 2.4\%$ after training, whereas the normalized EMG at the 50% MVC target force was $39.3 \pm 11.2\%$ before and $39.5 \pm 9.4\%$ after training. Similarly, there were no changes across time in the normalized EMG with each target load (5, 10, and 50%) for any group when performing the concentric and eccentric contractions ($P > 0.05$). The normalized EMG for the 50% 1-RM load during concentric contractions was $35.4 \pm 11.4\%$ before and $35.8 \pm 9.5\%$ after training. The normalized EMG during eccentric contractions with the 50% 1-RM load was $23.8 \pm 8.6\%$ before and $23.2 \pm 6.8\%$ after training, less than that during the concentric contractions ($P < 0.05$).

Physical Function Tests

There were no differences in usual gait speed, fastest gait speed, chair rise time, stair ascent time, or stair descent time between the three groups before training ($P > 0.05$). Sixteen weeks later, all groups exhibited small reductions in the time taken to perform the functional tasks (Table 5). There was no difference in the change between groups for each task ($P > 0.05$ for the group $\times$ time interaction). When the data for the groups were pooled, the changes were significant for usual gait speed ($P < 0.0001$) and chair rise ($P = 0.02$), but not for stair ascent ($P = 0.06$), fastest gait speed ($P = 0.16$), or stair descent ($P = 0.1$). The reduction in the composite score was significant (Table 5). There was no relation between the training-induced increase in 1-RM load and the reduction in time taken to perform any of the functional tasks ($P > 0.05$).

**DISCUSSION**

The purpose of the study was to determine the effect of strength and steadiness training by old adults on the fluctuations in force and position during voluntary contractions with the quadriceps femoris muscles. The 16 wk of training increased the maximal force, load-lifting capability, muscle volume, maximal surface EMG, and maximal force per unit muscle volume of the quadriceps femoris muscles. The force fluctuations during submaximal isometric contractions and the position fluctuations when lifting submaximal loads did not change with training. However, the force fluctuations during anisometric contractions with a 50% 1-RM load declined for both training groups over the course of the intervention, as did the force fluctuations measured only for the Heavy-Load Steady group during the training contractions with a 80% 1-RM load. Furthermore, the small gains in functional performance observed with training in these healthy older adults were not different from those experienced by the Control group.

**Comparison With Previous Training Studies**

Despite substantial strength gains, the training protocol did not influence the force fluctuations experienced by old adults, as a group, during isometric contractions that ranged from 2–50% MVC. This result contrasts with those for the first dorsal interosseus and ankle dorsiflexor muscles. Keen et al. (20) found that 12 wk of strength training with the first dorsal interosseus muscle by old adults increased the MVC force by 41% and reduced the force fluctuations at low forces (2.5, 5, and 20% MVC force). The decrease in force fluctuations occurred within the first 4 wk of training, whereas the strength gains accumulated linearly over the 12-wk intervention. Furthermore, the force fluctuations were reduced to levels exhibited by young adults, who did not experience any change in fluctuations in force during the training program. Laidlaw et al. (24) extended these findings by reporting that strength and steadiness training reduced force fluctuations during isometric and anisometric contractions with the first dorsal interosseus muscle. Although the strength gain was less for the subjects who performed light-load steadiness training, the reduction in the fluctuations was similar for the two groups. After 4 wk of training, the position fluctuations (standard deviation of index values)

<table>
<thead>
<tr>
<th>Group</th>
<th>Week 0</th>
<th>Week 8</th>
<th>Week 16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy-Load Steady ($n = 6$)</td>
<td>26.6±5.91</td>
<td>25.7±5.63</td>
<td>25.3±5.62*</td>
</tr>
<tr>
<td>Heavy-Load ($n = 11$)</td>
<td>30.2±5.14</td>
<td>28.9±5.91</td>
<td>27.6±5.51*</td>
</tr>
<tr>
<td>Control ($n = 9$)</td>
<td>28.9±5.21</td>
<td>28.3±5.95</td>
<td>27.4±5.04*</td>
</tr>
<tr>
<td>Pooled ($n = 26$)</td>
<td>28.9±5.31</td>
<td>27.9±5.76</td>
<td>27.0±5.23*</td>
</tr>
</tbody>
</table>

Values are means ± SD; $n$, no. of subjects. Composite physical function score is sum of the times for the timed gait speed, chair rise, stair ascent, and stair descent. *$P < 0.05$ compared with week 0.

**Fig. 6.** Fluctuations in position during concentric (A) and eccentric (B) contractions with 5, 10, and 50% 1-RM loads. Values compare the percent change in the standard deviation (SD) of knee position before training and 16 wk later. Changes were not significantly different from zero ($P > 0.05$). Values are means ± SE.
finger position) decreased by 25% with a 2.5% load and by 12% with a 20% load during concentric contractions and by 18 and 28%, respectively, during eccentric contractions. Moreover, Bilodeau et al. (2) reported that essential tremor patients who presented with the largest CV for force values experienced the greatest reductions in the fluctuations after 4 wk of strength training.

Similar effects have been observed in old adults after 2 wk of force- and position-tracking training with the dorsiflexor muscles. Patten and Kamen (27) found that the ability of young (18–22 yr) and old (66–76 yr) adults to match a force trajectory requiring modulation of force up to 60% MVC force improved after six training sessions over 2 wk. Although this intervention increased MVC force in young subjects, but not old subjects, there were no differences between the two groups of subjects, either before or after training, in the fluctuations in the force trajectory during the tracking task. Furthermore, both groups of subjects exhibited comparable reductions in the discharge rate of motor units during the force-tracking task. However, the old subjects decreased the amount of antagonist muscle coactivation with training, whereas the young subjects exhibited the converse. Similarly, Connelly et al. (3) found that old adults improved their ability to produce constant-velocity displacements of the ankle joint during sequences of concentric and eccentric contractions with the dorsiflexor muscles exerting moderate torques after six practice sessions. This improvement in performance was accompanied by an increase in the interference EMG for the tibialis anterior muscle and no change in activity for an antagonist muscle (soleus). Together, these findings indicate that strength training interventions consistently reduce fluctuations during low-to-moderate intensity contractions with distal muscles of the upper and lower limbs.

Two studies have examined the effect of strength training on force fluctuations during submaximal isometric contractions performed with the quadriceps femoris muscles by old adults. However, the substantial differences in design and data analysis between these studies and the present study prevent a meaningful comparison. For example, Bellew (1) found that 12 wk of participation in a general strength-training program increased MVC force for the old adults (59–83 yr) by 13% but was associated with no changes in the CV for force during isometric contractions at target forces of 30, 60, and 90% MVC force. The training exercises included a leg-press task and a knee-extension task, both of which involved isometric contractions with the quadriceps femoris muscles. The physical activity levels of the subjects are unknown, and the submaximal force targets did not include low forces. In the other study on quadriceps femoris, Hortobágyi et al. (18) reported that 10 wk of strength training (30 sessions) by old adults (66–83 yr) with either heavy (80% 1 RM) or moderate (40% 1 RM) loads reduced the force fluctuations during concentric and eccentric contractions, but not during isometric contractions. Subjects matched an absolute target force of 25 N on an isokinetic dynamometer before and after training; thus the target force relative to maximum was lower after training. The force fluctuations (SD) decreased by 40% during eccentric contractions and by 20% during concentric contractions. Because the relative target differed at these two time points, the net motor unit activity was less during the tests performed after training.

The results of the present study are consistent with the results reported in these two previous studies on quadriceps femoris but differ with the results for first dorsal interosseus. Taken together, the three studies on quadriceps femoris indicate that baseline differences in average force fluctuations between young and old adults (18, 35) can be attenuated with strength training during anisometric, but not isometric, contractions. In contrast to first dorsal interosseus, however, the improvement in performance was not expressed as a reduction in the standard deviation of position during anisometric contractions, probably because of a difference in the mechanical impedance of the two systems.

Specificity of Improvements in Performance

Although the data have been interpreted to indicate the presence of an adaptation in the amplitude of the force fluctuations during submaximal anisometric contractions, but not during isometric contractions, three qualifications are necessary. First, despite the absence of a group effect on the CV for force during isometric contractions, there was a range of responses exhibited by the old adults. In particular, subjects who had the greatest CV for force before training experienced the most substantial reduction in the force fluctuations at the two lowest target forces (Fig. 5). This effect was similar to that observed by Bilodeau et al. (2) in a group of patients with essential tremor. Whether the subjects in this study who responded to training by reducing force fluctuations exhibited preclinical tremor is speculative, but it is possible that strength training exerted an effect on the neural mechanisms that underlie physiological tremor in the lower limb. Furthermore, the relatively high physical function status of this subject sample is probably not responsible for the lack of an overall effect on the isometric contractions, because the fluctuations were reduced during anisometric contractions.

Second, the conclusion that the training intervention reduced the fluctuations during anisometric contractions is based on the observed decreases in the force fluctuations for the contractions performed during training with a 80% 1-RM load by the Heavy-Load Steady group (Fig. 3C) and the decreases in force fluctuations during concentric and eccentric contractions with the 50% 1-RM load during experimental contractions (Fig. 3D). Because force and acceleration provide a more sensitive measure of the mechanical output due to muscle activity than does limb position, greater emphasis is placed on the decline in the force fluctuations than the absence of a change in the position fluctuations. However, the training contractions were performed with loads of ~80% 1 RM by only the Heavy-Load Steady group and the experimental contractions where force fluctuations were measured involved 50% 1-RM loads. Thus generalizing the improvement in performance to lighter loads that involve different combinations of motor unit recruitment and rate coding is not justified. Nonetheless, this interpretation is consistent with the results of Hortobágyi et al. (18). It is acknowledged, however, that these results must be interpreted with caution because of the relatively low sample size in the Heavy-Load Steady group, which was intended as a subset of the training group to examine the potential additional effect of precise force control during training.

Third, all three groups of subjects displayed a small reduction in the time taken to complete the functional performance tasks after the 16-wk intervention. None of the changes in functional performance can therefore be directly attributed to
strength training. It is more likely that the marginal improvement in performance was due to a learning effect associated with repeat performances of the tasks. It is also possible that the lack of response in the functional tasks was due to the high baseline levels of function in this subject sample. For example, the subjects in the present study performed the standardized chair rise test more quickly (8.4 s) than another normative group of similar age (13.8 s) (14). As a consequence, it appears that performance on these tests was not limited by the strength of the quadriceps femoris muscles in this cohort of subjects.

Mechanisms Contributing to the Adaptations

The amplitude of the force fluctuations appears to depend on factors that influence either the summation of motor unit forces or the timing of the action potentials discharged by the motor neurons (9, 34). The adaptations in these mechanisms, however, are independent of those responsible for strength gains. For example, previous studies have found that the effects of training interventions on force fluctuations are not proportional to the changes in muscle strength (3, 24, 27). Furthermore, training can increase MVC force without reducing the force fluctuations (1, 18). In the present study, the average group increases in MVC force and 1-RM load were comparable, but there was no association between the relative increase in the two strength measures for each subject. Moreover, the changes in muscle strength and force fluctuations experienced by each subject were unrelated.

The three training studies on quadriceps femoris indicate that the mechanisms responsible for the fluctuations during anisometric contractions are amenable to adaptation with participation in a strength-training program, whereas the mechanisms underlying the fluctuations during isometric contractions are not. Both experimental measurements and computer simulations indicate that the force fluctuations during isometric contractions contain a prominent peak in the force power spectrum at ~1 Hz (34). In contrast, most of the power in an acceleration record during an anisometric contraction resides in an 8- to 10-Hz bandwidth (15, 19, 38). This difference suggests that the relative contributions of the mechanisms to the force fluctuations vary with contraction type. If this interpretation is correct, these intervention studies raise the interesting question of why both sets of mechanisms are influenced by training in the first dorsal interosseus muscle but not quadriceps femoris.

Presumably, the difference is related to the motor unit properties in the two muscles. Some of these differences include fewer motor units in the hand muscle (10, 12), a lesser upper limit of motor unit recruitment in the hand muscle (5, 7), greater direct corticospinal input to the motor neuron pool innervating the hand muscle (8), and a greater amount of synchronization between pairs of motor units in hand muscles compared with leg muscles (4). Furthermore, the discharge properties of motor units in hand muscles will adapt in response to various interventions (7, 22, 31), whereas the adaptive capacity of motor units in quadriceps femoris appears to be reduced (28, 29). Although the present study did not examine the motor unit properties that are responsible for the apparent contraction-type specificity in the training response exhibited by the quadriceps femoris muscles of old adults, these findings suggest that the mechanisms responsible for changes in force fluctuations with training are not shared between anisometric and isometric contractions or between the quadriceps femoris muscles and the first dorsal interosseous muscle.

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