Strength training improves the steadiness of slow lengthening contractions performed by old adults

DOUGLASS H. LAIDLAW,1 KURT W. KORNATZ,1 DOUGLAS A. KEEN,2 SHUJI SUZUKI,3 AND ROGER M. ENOKA1

1Department of Kinesiology and Applied Physiology, University of Colorado, Boulder, Colorado 80309; 2Department of Physiology, University of Arizona, Tucson, Arizona 85721; and 3Department of Sport Sciences, Waseda University, Tokorozawa, Japan 359-1192

Strength training improves the steadiness of slow lengthening contractions performed by old adults. J. Appl. Physiol. 87(5): 1786–1795, 1999.—When old adults participate in a strength-training program with heavy loads, they experience an increase in muscle strength and an improvement in the steadiness of submaximal isometric contractions. The purpose of this study was to determine the effect of light- and heavy-load strength training on the ability of old adults to perform steady submaximal isometric and anisometric contractions. Thirty-two old adults (60–91 yr) participated in a 4-wk training program of a hand muscle. Both the light- and heavy-load groups increased one-repetition maximum and maximal voluntary contraction (MVC) strength and experienced similar improvements in the steadiness of isometric and shortening and lengthening contractions. The increase in MVC strength was greater for the heavy-load group and could not be explained by changes in muscle activation. Before training, the lengthening contractions were less steady than the shortening contractions with the lightest loads (10% MVC). After training, there was no difference in steadiness between the shortening and lengthening contractions, except with the lightest load. These improvements were associated with a reduced level of muscle activation, especially during the lengthening contractions.

Metho

Experiments were performed on the left hand of 32 old adults (19 women, 13 men; 60–91 yrs) with no known neuromuscular disorders. Subjects were randomly assigned to one of three groups: a heavy-load training group (4 women, 4 men; mean ± SE: 68.3 ± 2.2; range: 60–78 yr), a light-load training group (4 women, 4 men; mean ± SE: 70.4 ± 2.0; range: 62–77 yr), and a control group (11 women, 5 men; mean ± SE: 72.4 ± 1.7; range: 62–90 yr). Each subject participated in five experimental sessions that comprised an initial experiment and one experiment after each of four consecutive weeks. The Human Subjects Committee at the University of Colorado approved all experimental procedures, and all subjects gave their informed consent before participation in the study.

The muscle tested in this study was the first dorsal interosseus, which is located between the thumb and index finger and is especially active during the pinch grip (6). This muscle controls abduction of the index finger away from the longitudinal axis of the hand and contributes as a synergist to flexion of the metacarpophalangeal joint of the index finger. It is a flat, triangular muscle with two heads that are separated by a fibrous arch. The radial head arises from the dorsal surface of the ulnar border of the first metacarpal, whereas the radial head arises from the proximal three-quarters of the radial border of the second metacarpal. The common tendon attaches to the radial side of the proximal phalanx of the index finger (7). It is relatively easy to record the electrical activity by means of surface and intramuscular electrodes without significant interference from neighboring muscles and to record the abduction force exerted by the index finger due solely to the action of the first dorsal interosseus muscle (4).

Experimental Setup

The experiments were conducted with the subjects seated and facing an oscilloscope, which was positioned 1.2 m away,
at the level of the subject's eyes. For the isometric and anisometric tasks, the index finger was placed in an individualized polyvinyl silicone mold and strapped inside an L-shaped delryn splint. The splint was placed along the lateral and ventral surfaces of the index finger to keep the interphalangeal joints extended. The left arm was abducted, with the elbow joint flexed at a right angle. The hand and forearm were placed prone and restrained with several devices on a manipulandum, as described previously (13).

Mechanical Recording

Isometric contractions. With the hand positioned in the manipulandum so that the index finger was abducted 5° from the neutral position, a force transducer (Sensotec model 13) attached to the delryn splint detected the abduction force at the proximal interphalangeal joint. The sensitivity of the force transducer used during the high-force tasks was 0.053 V/N (linear range: 0–220 N), whereas more sensitive force transducers (0.54 V/N, linear range 0–22 N; 1.01 V/N, linear range 0–9.81 N) were used for the low-force tasks.

Anisometric contractions. A low-friction, linear variable differential transducer (LVDT; Novotechnik) was used to detect the abduction displacement of the index finger about the first metacarpophalangeal joint. The LVDT was mounted on an extended delryn platform, and it was positioned perpendicular to the index finger in the initial position (5° abduction). This configuration minimized the error in the linear recording of angular motion. The LVDT was attached to the delryn splint with a low-friction, ball-and-socket joint, allowing for free movement of the index finger through its range of motion (10°). The LVDT was calibrated for each subject and session over the range of motion.

Electrical Recording

The electromyogram (EMG) of the left first dorsal interosseus muscle was recorded with bipolar surface electrodes (4-mm diameter; silver-silver chloride) that were positioned ~8 mm center-to-center apart on the skin overlaying the midbelly of the muscle. A common electrode (4-mm diameter; silver-silver chloride) was placed on the styloid process of the ulna on the dorsal surface of the hand. The surface EMG signals were amplified (1,000–10,000 times), band-pass filtered (20–800 Hz), and displayed on an oscilloscope.

Experimental Procedures

Each of the 32 subjects was asked to perform four tasks with the index finger and the first dorsal interosseus muscle: 1) isometric maximum voluntary contractions (MVC) in the abduction direction; 2) evoked responses (whole muscle twitches and M waves); 3) isometric constant-force trials; and 4) anisometric constant-load trials. The isometric tasks were performed with the index finger in the neutral position.

MVC. The MVC task consisted of a gradual increase in the abduction force exerted by the index finger from baseline to maximum in 3–4 s and then sustained at maximum for 1–2 s. The timing of the task was based on a verbal count given at 1-s intervals, with vigorous encouragement from the investigators when the force trace began to plateau. One or two practice trials were performed before two MVC trials. Subsequent trials were performed if the difference between the first two MVCs was >5%. The trial with the greatest peak force was used for analysis. The subjects rested for 60–90 s between consecutive trials.

Evoked responses. The M waves and twitches were elicited in first dorsal interosseus by percutaneous stimulation of the ulnar nerve at the wrist. Three responses were evoked in a relaxed muscle by supramaximal electrical stimuli (0.1-ms duration, 0–240 V) that were provided by a Grass S-8800 stimulator in series with a Grass SIU8T stimulus isolation unit. The shocks were delivered through a bipolar electrode that was placed on the ventromedial aspect of the forearm. The electrode was placed 3–5 cm proximal to the wrist joint. The cathode was positioned at the location that maximized the peak-to-peak amplitude of the M wave. Once the cathode position was determined, the electrode was held firmly in place, and the stimulus intensity was increased to a supramaximal level. A response was elicited every 3 s.

Constant-force task. Target forces were set at 2.5, 5, 10, and 20% of MVC force. The subjects gradually increased the abduction force during an isometric contraction to the target force displayed on the oscilloscope and held the force steady at the target force for 30 s. The sensitivity of the force display was set relative to the target force so that the distance from the baseline to target force was three to four vertical divisions on the oscilloscope. The subjects performed one trial at each target force. The order of the trials was varied.

Constant-load task. A weight that matched the target force for the constant-force task was attached to a line and connected to the splint at the proximal interphalangeal joint, providing a load in the adduction direction. Three trials were performed with the index finger moving through a 10° range of motion from the neutral position. The subjects raised and lowered the weight during 6 s of abduction and 6 s of adduction, respectively. A triangular template was displayed on the oscilloscope, and the subject was given three practice trials to become familiar with the timing and amplitude of the index finger movement. The subjects were instructed to match the index finger displacement with the desired template as closely as possible.

Strength Training

The two training groups participated in a 4-wk strength-training program with the first dorsal interosseus muscle. The hand was restrained, with the palm facing down on a training device (13) that was designed to allow abduction of the index finger against a load. Hand position was maintained by restraints for both the middle finger and thumb. With this setup, the range of motion at the second metacarpophalangeal joint was reduced, not permitting any adduction beyond the neutral position. A splint on the index finger was secured at the proximal interphalangeal joint to a string through a pulley and attached to the load. Each subject used a custom-fitted board, so that the position of the hand and digits remained constant.

The subjects trained three times per week for 4 wk. Each training session comprised 6 sets of 10 repetitions, with each repetition comprising the entire range of motion in the abduction-adduction plane (~20°). The training loads were based on the maximum load that the index finger could lift one time [one-repetition maximum (1-RM) load] by contracting the first dorsal interosseus muscle. The heavy-load group performed the movement against 80% of the 1-RM load, and the light-load group used 10% of the 1-RM load. The 1-RM load was measured weekly, and the training loads were set accordingly. Additionally, a metronome set to 40 beats/min was used during training to standardize the timing of the finger movements so that the shortening and lengthening contractions each lasted ~1.5 s. All training was performed in the laboratory under supervision.

Data Analysis

All data collected during the experiments were recorded and stored in digital format (Sony PC 116 DAT recorder;
The dependent variables for the MVC task were peak abduction force and the average of the full-wave rectified EMG (AEMG) for a 0.5-s window centered at the peak force. For the evoked responses, the average of the three trials was used for each dependent variable: 1) peak-to-peak-amplitude of the M wave; 2) peak twitch force; 3) time to peak twitch force (contraction time); and 4) one-half relaxation time. The M-wave amplitude was used to assess the relative activation of the first dorsal interosseus muscle during the MVC task.

The dependent variables for the constant-force task were SD of the force fluctuations within a 20-s window, coefficient of variation of the force (SD/mean force × 100), and AEMG in a 2-s window when the force was relatively constant.

For the constant-load task, the steadiness of the movement was determined by measuring the variations in position about the average movement velocity. Least squares regression was used to determine the average velocity, and the slope of the regression line was subtracted from the data to remove the trend (average velocity) from the position data. The detrending procedure resulted in a more conservative measure of fluctuations in position, because the magnitude of the SD is always lower when measured perpendicular to the average velocity. The dependent variables were maximum abduction of the index finger, average movement velocity, and SD of the detrended position data for the entire (~6-s) and middle (4-s) phases of the shortening and lengthening contractions. The middle 4 s were analyzed to remove the end effects of each phase; that is, the onset of movement with a shortening contraction, the transition from the shortening to the lengthening contraction, and the completion of the lengthening contraction. Additionally, separate analyses were performed on the steadiest performance (the minimum SD) of each phase, for each subject and load condition within a session.

Statistical Analysis

A two-factor ANOVA (StatView, SAS Institute) with a repeated-measures design (1 factor between and 1 within) was used to compare the dependent variables for the MVC and evoked responses between the three groups, across sessions, and the group-by-session interaction. A two-factor ANOVA (1 factor between and 1 within) was used to compare the constant-force and constant-load dependent variables between groups, across forces/loads, and the group-by-force/load interactions. A three-factor ANOVA with two repeated-measures (1 factor between and 2 within) was applied to the constant-load data to compare the dependent variables between groups, across sessions and contraction type, and their interactions. An α level of 0.05 was chosen for all initial statistical comparisons, with multiple comparisons performed when necessary to determine between-group, force/load, and contraction type (shortening vs. lengthening) differences. All results are reported as means ± SE.

RESULTS

The effects of the light- and heavy-load training were determined after 1, 2, 3, and 4 wk of training and were compared with data obtained before the beginning of training and with the control group. Before training, there were no between-group differences for any of the dependent variables. The main findings of the present study were that both light- and heavy-load training caused an increase in 1-RM load and MVC force and an increased ability to perform steady, low-force isometric and slow shortening and lengthening contractions (Fig. 1).

Strength Tasks

There were no between-group differences for the 1-RM load or the MVC force before training. The initial strength values for all 32 subjects were 10.3 ± 0.8 N for the 1-RM load and 28.7 ± 1.4 N for the MVC force. Although the men were initially stronger than the women in both the 1-RM load (11.9 ± 1.0 vs. 9.3 ± 0.5 N) and MVC force (33.5 ± 1.8 vs. 25.4 ± 1.8 N), there was no interaction between group and gender on the initial strength measurements.

Both the light- and heavy-load groups experienced significant strength gains in 1-RM load and MVC force after 4 wk of training (Table 1 and Fig. 2). The 1-RM
load increased by 38.1 ± 4.2% for the heavy-load group and by 22.8 ± 5.7% for the light-load group (Fig. 2A); these increases were not statistically different (Table 1). MVC force increased by 44.2 ± 8.4% for the heavy-load group, which was greater than the 13.0 ± 5.1% increase achieved by the light-load group (Fig. 2B). Comparisons of strength gains for men and women experienced similar strength gains in 1-RM load and MVC force after 3 wk of training (13.3 ± 5.1% in the heavy-load group, which was greater than the 13.0 ± 5.1% increase achieved by the light-load group (Fig. 2B)). Comparisons of strength gains for men and women within the two groups showed that both men and women experienced similar strength gains in 1-RM load and MVC force; that is, there was no group-by-gender interaction. Men in the heavy-load group increased 1-RM load by 24.7 ± 6.3%, and the women experienced an increase of 20.9 ± 10.5%. Similarly, the gains in MVC force were 16.6 ± 7.3% for the men and 10.3 ± 7.7% for the women. The men in the heavy-load group demonstrated gains of 40.9 ± 7.3% in the 1-RM load and 55.3 ± 13.3% in the MVC force, whereas the gains for the women were 35.3 ± 5.0% for 1-RM load and 32.9 ± 8.5% for MVC force.

Figure 2 illustrates that there were differences between the two training groups in the time course of the strength gains. The heavy-load group had a 16.7 ± 5.0% gain in 1-RM load after 1 wk and a 28.1 ± 9.5% increase in MVC force after 3 wk. The increase in MVC force after the second week of training was substantial but not statistically significant (19.2 ± 13.2%, P = 0.08). In contrast, the 1-RM load for the light-load group increased after 3 wk of training (13.3 ± 6.6%), whereas the gains in MVC force were not evident until the fourth week (13.0 ± 5.1%). Analysis of covariance indicated that the relationship between 1-RM load and MVC force was the same for the three groups of subjects before and after the training program. This indicated that the strength gains observed for a given subject were similar for the two strength measures. Figure 2C shows that the linear relationship between 1-RM load and MVC force for the subjects in the light- and heavy-load groups was similar before and after training.

Because there was no increase in strength for the control subjects, the reliability of subject performance and experimental conditions across the five experimental sessions was assessed for 1-RM load and MVC force. The intraclass correlation coefficients (25) for 1-RM load and MVC force across the five sessions were 0.98 and 0.93, respectively. This analysis indicated that, for individual subjects, the two strength measurements were highly reliable across the five sessions.

There were no between-group differences or any changes in the absolute AEMG for first dorsal interosseus across the five experimental sessions (Fig. 3). To reduce some of the variability in EMG measurements due to differences in skin impedance and electrode placement between subjects and across sessions, the AEMG amplitude was normalized to the amplitude of the evoked compound muscle action potential (M wave). Despite this adjustment, there were no group differences or changes in the normalized AEMG amplitude across the five experimental sessions (Fig. 3). Therefore, the group factor was collapsed, and the reliability of the AEMG measurement was assessed. The intraclass correlation coefficient for normalized first dorsal interosseus AEMG across the five sessions was 0.88.

**Evoked Responses**

As reported previously (10), there were no differences between the three groups of subjects in the magnitude and time course of the evoked responses, either before or after training. Before training, the peak twitch force was 2.17 ± 0.29, 2.36 ± 0.22, and 2.04 ± 0.22 N for the control, light-load, and heavy-load groups, respectively. The initial twitch contraction time was 67.2 ± 3.2, 71.1 ± 4.9, and 72.1 ± 4.8 ms for the control, light-load, and heavy-load groups, respectively. Similarly, one-half relaxation time was 63.7 ± 3.9, 82.3 ± 5.5, and 77.5 ± 5.2 ms for the control, light-load, and heavy-load groups, respectively. When the group factor was collapsed, the average initial values were 2.15 ± 0.16 N, 70.2 ± 2.0 ms, and 71.4 ± 2.8 ms for twitch force, contraction time, and one-half relaxation time, respectively. There was no effect of gender on any of the evoked-response measurements.

When the reliability across sessions was assessed for the evoked responses, the intraclass correlations were 0.95, 0.87, and 0.81 for twitch force, twitch contraction time, and one-half relaxation time, respectively. These data suggest that the recording conditions from session...
to session were similar and did not contribute to the strength gains or improvements in steadiness found in this study.

Constant-Force Task

There were no differences between the three groups of subjects in any of the initial measures of steadiness. As others have reported (8, 13), the SD of force fluctuations increased linearly as a function of force for all subjects from 64.9 ± 5.9 mN at the target force of 2.5% to 204 ± 12.4 mN at the target force of 20% (SD = 36.9 + 28.5 × target force, $r^2 = 0.68$, $P < 0.0001$). When the force fluctuations were normalized to the target force, however, the coefficient of variation decreased from 7.26 ± 0.43% at the target force of 2.5% to 3.55 ± 0.20% at the target force of 20%.

The ability of the control subjects to produce steady, isometric contractions at submaximal levels did not change in the five experimental sessions over the duration of the training program. In contrast, both the light- and heavy-load groups improved steadiness significantly (Table 2, Fig. 4). For example, after 4 wk of training, the coefficient of variation was reduced by ~14% at the target forces of 2.5 and 5% and by ~32% at the target forces of 10 and 20% for the light-load group. Furthermore, there was a 34% decrease in the SD of the force fluctuations at the 20% force. Similarly, for the heavy-load group, the coefficient of variation for the force fluctuations declined by 34–47% for the four target forces after training, compared with before training. Moreover, the SDs at the target forces of 2.5 and 20% were reduced by 18 and 32%, respectively, after training.

For the two training groups combined, most of the improvement in the steadiness of the isometric contractions occurred in the first week of training (Fig. 4). Over this interval, the absolute and normalized fluctuations declined by 10–25% across the target forces. For the highest target force, however, steadiness continued to improve over the course of the training program.

Before and after training, the amount of muscle activity during the constant-force contractions was not different for the three groups when performing the isometric tasks. Furthermore, there were no significant training-related changes in AEMG (%MVC). When the group factor was collapsed, the normalized AEMG for first dorsal interosseus before training was 5.91 ± 0.44, 9.17 ± 0.56, 14.9 ± 0.84, and 27.4 ± 2.25% for the 2.5, 5, 10, and 20% forces, respectively. These results pro-

Fig. 2. Strength measurements over 4 wk of training for control, light-load, and heavy-load training subjects. Data shown represent means ± SE. Whereas there were no changes for control group, both light- and heavy-load training groups had significant gains in 1-repetition maximum (1-RM) load (A) and MVC force (B) after 4 wk of training. Relationship between 1-RM load and MVC force for light- and heavy-load training subjects across the 5 experimental sessions was linear (C). Each data point represents MVC force and 1-RM data for an individual subject either before (open symbols) or after (closed symbols) training. Dashed regression line is for the before-training data, and solid regression line is for the after-training data. Regression lines were not significantly different from each other.

Fig. 3. Absolute (○; mV) and normalized (●; %M-wave amplitude) average electromyogram (AEMG) amplitude for 1st dorsal interosseus muscle during isometric MVCs over 4 wk of training. Because there were no between-group differences, group factor was collapsed (n = 32). Data shown represent means ± SE. These data suggest that gains in MVC force were not due to an increase in amount of activity in 1st dorsal interosseus.
duced a linear relationship between AEMG and target force ($AEMG = 2.11 + 1.23 \times target\ force, r^2 = 0.60, P < 0.0001$). Similarly, after training, there were no group differences, and the relationship between the normalized AEMG and target force was comparable to that before training ($AEMG = 3.66 + 1.22 \times target\ force, r^2 = 0.63, P < 0.0001$).

**Constant-Load Task**

After 4 wk of training, both the light- and heavy-load groups were steadier with slow shortening and lengthening contractions, compared with the control subjects (Fig. 5). Because there were no differences in the responses of the two training groups with the constant-load task, the data for the light- and heavy-load groups were pooled for comparison with the control subjects. Before training, there were no between-group differences (control vs. trained) across all four loads in the average or minimum SD of position about the average velocity during the shortening and lengthening contractions. Furthermore, there were no differences across the four loads in the measure of steadiness (Table 3). When the before-training data were collapsed across loads and averaged across the three trials for the 32

| Table 2. Absolute (SD) and normalized (CV) amplitude of force fluctuations during submaximal isometric constant-force contractions |
|---|---|---|---|---|---|---|---|---|
| | Control | Light | Heavy |
| **2.5% Force** | | | |
| SD, mN | 63.2±10.2 | 69.5±15.3 | 59.8±6.6 |
| CV, % | 7.3±0.69 | 6.94±1.34 | 7.33±0.37 |
| **5% Force** | | | |
| SD, mN | 89.5±14.2 | 77.4±17.8 | 79.3±13.1 |
| CV, % | 6.04±0.72 | 4.45±0.81 | 4.81±0.62 |
| **10% Force** | | | |
| SD, mN | 128.7±16.6 | 116.3±11.8 | 103.8±14.4 |
| CV, % | 4.30±0.36 | 3.53±0.40 | 3.68±0.36 |
| **20% Force** | | | |
| SD, mN | 203.5±23.1 | 202.2±10.4 | 200.9±20.1 |
| CV, % | 3.67±0.35 | 3.47±0.31 | 3.58±0.24 |

Values are group means ± SE for before (week 0) and after (week 4) training. CV, coefficient of variation. *P < 0.05, after vs. before training; †P < 0.05, light vs. control, heavy vs. control.
subjects, the SD for the entire 6 s of the shortening contractions was 0.52 ± 0.01°. In contrast, the SD for the lengthening contractions was 0.61 ± 0.02°, which was significantly greater than the value for the shortening contractions. When the movement transitions were removed, and the data for the middle 4 s of each contraction were examined, the results were similar, with the lengthening contraction less steady than the shortening contraction (0.34 ± 0.01° vs. 0.41 ± 0.02°). These relationships were similar when the comparisons were based on the trials with the minimum SD.

There were no changes in any of the dependent variables for the constant-load task over the 4 wk of the study for the control group. In contrast, both the light- and heavy-load groups had similar and significant improvements in the ability to perform slow, steady shortening and lengthening contractions with the first dorsal interosseus muscle (Fig. 5). For example, after 4 wk of training, the average SD for the shortening contractions declined by 25% for the 2.5% load and by 12% for the 20% load. Similarly, there were declines of 18 and 28% in the SDs for the lengthening contractions at these two loads. These effects were similar for both the average and minimum SDs with all four loads.

The training-related improvement in steadiness was not due to changes in the amplitude or the average velocity of the movements in either phase of the task (shortening or lengthening contraction) or with any load. For the subjects who performed the strength training, the average amplitude of index finger displacement was 10.1 ± 0.1° during the constant-load task. The average velocity was 1.43 ± 0.01°/s for the shortening contraction and −1.40 ± 0.02°/s for the lengthening contraction.

Before training, there were no group differences in AEMG for the first dorsal interosseus muscle during the constant-load contractions. Whereas the level of muscle activity during the shortening and lengthening contractions did not change for the control subjects over the 4 wk, there were significant training-related de-

![Fig. 5. Training-related changes in steadiness of shortening (○), and lengthening (■) contractions at all loads over time for training group subjects. Trend was similar for the average (A) and minimum (B) SD of position during shortening and lengthening contractions before (open symbols) and after (closed symbols) 4 wk of training. There were no significant changes for control group. In contrast, training groups generally exhibited parallel changes in steadiness of shortening and lengthening contractions over 4 wk of training. Because there were no differences between training groups, data for the light- and heavy-load groups were combined and indicate means ± SE. Average SDs (A) for shortening and lengthening contractions at all loads were reduced after 4 wk of training. Except for shortening contractions with the 20% load, the minimum SDs (B) were also reduced after training. Furthermore, absolute training-related changes were typically greatest for lengthening contractions compared with shortening contractions.

### Table 3. SD of position during the middle 4 s of the shortening and lengthening contractions

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>trained</th>
<th>%Change</th>
<th>Control</th>
<th>trained</th>
<th>%Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
<td></td>
<td>Before</td>
<td>After</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>L</td>
<td></td>
<td>S</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.31±.04</td>
<td>0.38±.03†</td>
<td>0.29±.02</td>
<td>0.40±.05†</td>
<td>0.4±.75</td>
<td>6.8±.126</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.21±.04</td>
<td>0.28±.02†</td>
<td>0.19±.01</td>
<td>0.29±.03†</td>
<td>−1.4±.81</td>
<td>10.9±.133</td>
</tr>
<tr>
<td>5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.33±.03</td>
<td>0.46±.08†</td>
<td>0.30±.03</td>
<td>0.37±.04†</td>
<td>−9.7±.69</td>
<td>−5.1±.104</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.22±.01</td>
<td>0.31±.05†</td>
<td>0.19±.02</td>
<td>0.26±.03†</td>
<td>−16.6±.73</td>
<td>3.7±.144</td>
</tr>
<tr>
<td>10%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.34±.03</td>
<td>0.46±.06†</td>
<td>0.30±.04</td>
<td>0.34±.03†</td>
<td>−6.7±.81</td>
<td>−2.6±.201</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.24±.02</td>
<td>0.29±.03†</td>
<td>0.21±.02</td>
<td>0.25±.02†</td>
<td>−3.6±.115</td>
<td>−9.0±.112</td>
</tr>
<tr>
<td>20%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.42±.04</td>
<td>0.37±.04</td>
<td>0.38±.05</td>
<td>0.38±.03</td>
<td>−2.7±.98</td>
<td>9.7±.91</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.26±.02</td>
<td>0.29±.03</td>
<td>0.24±.02</td>
<td>0.26±.04</td>
<td>−4.8±.69</td>
<td>3.3±.148</td>
</tr>
</tbody>
</table>

Values are group means ± SE for average and minimum values before (week 0) and after (week 4) training. Group comparisons represent differences in changes in SD (SD of position in °). S, shortening; L, lengthening. *P < 0.05, after vs. before training; †P < 0.05, shortening vs. lengthening contractions; ‡P < 0.05, trained vs. control.
increases in AEMG, especially during the lengthening contractions (Fig. 6). For example, the normalized AEMG declined between 35 and 42% during the lengthening contractions with the four loads. In contrast, only the 32% reduction for the shortening contraction with the 20% load was significant; the declines of 22–29% with the lighter loads were not statistically significant.

DISCUSSION

The main findings of this study were that 4 wk of strength training when the subjects were using light or heavy loads increased the strength of a hand muscle in old adults and improved their ability to perform steady, low-force isometric and slow shortening and lengthening contractions. The increases in strength and the steadiness of isometric contractions could not be explained by changes in the average level of muscle activation. However, the improvements in steadiness during the anisometric contractions were associated with a reduced level of activation of the first dorsal interosseus muscle, especially during the lengthening contractions.

Increases in Strength

Four weeks of strength training the first dorsal interosseus muscle with light or heavy loads resulted in significant gains in MVC and 1-RM strength. The magnitudes of the strength gains, however, were different for the two groups. The subjects who trained with a heavy load experienced similar gains in 1-RM load and MVC force (38 and 44%). In contrast, we previously found that the increase in 1-RM load (49%) was much greater than the increase in MVC force (14%) when old adults performed a strength-training program (12). It appears to be more common that the gain in 1-RM load is greater than that for MVC force after participation in a strength-training program, which is usually interpreted to indicate a significant role for coordination in the improvement in performance (11, 21).

One possible explanation for the greater gains in MVC force relative to 1-RM load found in the present study might be the level of constraint imposed on the subjects during training. All training was performed in the laboratory under supervision, with strict control of hand position, the timing of each repetition, and the range of motion. Because the goal of both the training and the testing sessions was to isolate the function of the first dorsal interosseous muscle, the task was highly constrained. The literature suggests that the specificity of a strength gain is most evident when the training involves movements that are minimally constrained (21–23).

In contrast to the comparable gains in MVC force and 1-RM load achieved by the heavy-load group, the light-load group realized a greater increase in 1-RM load (23%) than MVC force (13%). The relative increase in 1-RM load for the light-load group, which trained with loads that were 10% of the 1-RM load, was not statistically different from that for the heavy-load group. However, the heavy-load group experienced a greater increase in MVC force (44 vs. 13%). Several groups have examined the effects of exercising with light loads. In general, these results have been mixed, with some groups finding a significant training effect and others not (1, 2, 18, 20). However, light-load training that focuses on the control of movement does appear to have some positive effects on the performance capabilities of older adults (2, 17, 24).

The change in MVC force over the course of the 4-wk training program was similar for the control and light-load groups (Fig. 2B), which seems reasonable because they performed the same number of MVCs. The increase in 1-RM load, however, was greater for the light-load group compared with the control group (Fig. 2A). This difference suggests that, although the two groups performed the 1-RM task about the same number of times, the 12 training sessions with the light load (10% 1-RM) appear to have improved the ability of the light-load group to perform this task. Given the magnitude of the training load and the duration of the program, it is likely that the improvement in performance was mediated by adaptations in the activation of the muscle by the nervous system (22).

Constant-Force and Constant-Load Tasks

Keen et al. (13) found that old adults experienced a decrease in the magnitude of normalized force fluctuations during isometric contractions after participating in a 12-wk strength training program with heavy loads. They were, however, unable to distinguish between increases in strength and practice as being responsible for the improvement in steadiness. In the present study, we used light- and heavy-load training, along with a control group, to distinguish between the effects of strength training and practice on the ability of old adults to perform steady submaximal contractions.

The steadiness of isometric contractions, as indicated by the SD and coefficient of variation of the force
fluctuations, improved over the duration of the training program in both the light- and heavy-load groups. The improvement in steadiness was similar for the two training groups, which suggests that the increase in strength per se probably played a minimal role in the adaptation. Two findings underscore this conclusion. First, there were no changes in the steadiness of isometric contractions in the control group, which performed an equal number of isometric contractions over the five experimental sessions to the subjects in the training groups. Second, the two training groups performed an equal number of contractions in the training and testing sessions. The improvement in steadiness, therefore, was most likely due to a transfer effect from the slow anisometric contractions performed in the training program.

The similar improvements for the light- and heavy-load groups, but not the control group, in the steadiness of the shortening and lengthening contractions further support the notion of a training effect. The nature of the training effect was that, even though the loads lifted increased over the 4 wk of training, the AEMG during the shortening and lengthening contractions actually declined, especially during the lengthening contractions. In contrast, there were no changes in the load or EMG activity in the control group. Because old adults tend to coactivate the antagonist muscle (second palmar interosseus) more than young adults during anisometric contractions (3), it is likely that the paradoxical changes in load and AEMG for first dorsal interosseus can be explained by a training-related reduction in coactivation of the antagonist muscle.

Because there were no between-group or across-session differences in the AEMG amplitude during the isometric tasks, it is difficult to identify, based on these data, the mechanisms underlying the improvement in steadiness during the constant-force contractions. However, Laidlaw et al. (15) found that the reduced steadiness of low-force isometric and slow shortening and lengthening contractions in old adults was associated with an increased variability in the discharge rate of motor units. Given that the maximum discharge rate of motor units at high forces is less in older adults (5, 12) and that it increases with training (19), a significant role for changes in motor unit behavior seems possible.

It should be noted that it is unlikely that the first dorsal interosseus muscle experiences a significant number of lengthening contractions during daily use. However, recent studies in our laboratory have confirmed that our findings on the steadiness of low-force isometric, shortening, and lengthening contractions generalize to a larger range of loads (2.5–75% 1-RM), and for other muscles: first dorsal interosseus (1); the elbow flexor group (3); and the knee extensor group (unpublished observations). Thus the observation that old adults have a reduced ability to perform steady muscle contractions, especially lengthening contractions, is not an epiphenomenon and likely has functional significance for normal human movements.

In conclusion, a 4-wk strength-training program of a hand muscle resulted in significant strength gains whether subjects trained with light or heavy loads. The increases in MVC force were greater for the subjects who trained with heavy loads, but the increases in 1-RM load were similar for the two groups. The strength gains could not be explained by an increase in the surface-recorded EMG activity. Furthermore, both groups improved their ability to perform steady low-force isometric and light-load anisometric contractions. The magnitude of the improvements in steadiness was similar for the two groups. In contrast to the isometric contractions, the improvements in steadiness of the anisometric contractions were associated with reduced muscle activity, especially during the lengthening contractions.

This work was supported by National Institute on Aging Grant AG-09000 (to R. M. Enoka).

Address for reprint requests and other correspondence: R. M. Enoka, Dept. of Kinesiology and Applied Physiology, Univ. of Colorado, Boulder, CO 80309-0354 (E-mail: roger.enoka@colorado.edu).

Received 21 june 1999; accepted in final form 5 August 1999.

REFERENCES