

Effects of combined endurance and strength training on muscle strength, power and hypertrophy in 40–67-year-old men

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Both strength and endurance training have several positive effects on aging muscle and physical performance of middle-aged and older adults, but their combination may compromise optimal adaptation. This study examined the possible interference of combined strength and endurance training on neuromuscular performance and skeletal muscle hypertrophy in previously untrained 40–67-year-old men. Maximal strength and muscle activation in the upper and lower extremities, maximal concentric power, aerobic capacity and muscle fiber size and distribution in the vastus lateralis muscle were measured before and after a 21-week training period. Ninety-six men [mean age 56 (SD 7) years] com-

pleted high-intensity strength training (S) twice a week, endurance training (E) twice a week, combined training (SE) four times per week or served as controls (C). SE and S led to similar gains in one repetition maximum strength of the lower extremities [22 (9)% and 21 (8)%, $P < 0.001$], whereas E and C showed minor changes. Cross-sectional area of type II muscle fibers only increased in S [26 (22)%, $P = 0.002$], while SE showed an inconsistent, non-significant change [8 (35)%, $P = 0.73$]. Combined training may interfere with muscle hypertrophy in aging men, despite similar gains in maximal strength between the strength and the combined training groups.

Loss of skeletal muscle mass due to aging is usually associated with decreased muscle strength and a decline in functional capacity (Hunter et al., 2004), which start in middle-age and gradually accelerate thereafter (Deschenes, 2004). Strength training improves muscle strength and power through several mechanisms, for example increasing voluntary activation of trained muscles and inducing changes in the muscle cross-sectional area (CSA) and subtypes of muscle fibers, even when strength training begins in older age (Häkkinen et al., 1998a, 2001; Kryger & Andersen, 2007). Therefore, with strength training, it is possible to prevent or delay the age-related loss of skeletal muscle mass and decreases in muscle strength and power in middle-aged and older individuals (Hunter et al., 2004; Martel et al., 2006).

In contrast to strength training, a typical endurance training program improves aerobic capacity (Coggan et al., 1992), and has several favorable effects, for example on cardiovascular risk factors in the aging population, particularly when the training intensity is sufficient (Cornelissen et al., 2009).

Endurance training usually results in increased mitochondrial content, capillary density and aerobic enzyme activity (Holloszy & Coyle, 1984). The physiological effects of endurance training on skeletal muscle have thus been suggested to be antagonistic to increases in strength and muscle CSA, particularly in muscle fibers that are recruited to perform both types of exercise (Hickson, 1980; Kraemer et al., 1995; Bell et al., 2000). It has been shown previously in young subjects that high-intensity running endurance training may even decrease the area of type I (Kraemer et al., 1995) and type II muscle fibers (Trappe et al., 2006). However, the effects of endurance training on skeletal muscle are highly dependent on the intensity, volume and mode of training.

Because of the specific effects of strength and endurance training, a well-designed combination of these two training modes could potentially minimize the negative effects of aging more extensively than either alone (Ferketich et al., 1998). When the volume, frequency and duration of combined training are moderate, strength or endurance performance

do not seem to be compromised with concurrent strength and endurance training in young adults (McCarthy et al., 1995, 2002; Häkkinen et al., 2003; Izquierdo et al., 2005). However, high volume and prolonged combined training has been shown to interfere with strength gains (Hickson, 1980; Dudley & Djamil, 1985; Bell et al., 1997), muscle hypertrophy (Kraemer et al., 1995; Bell et al., 2000) and occasionally aerobic capacity (Nelson et al., 1990), compared with the same type and volume of strength or endurance training only. Concurrent endurance training may inhibit muscle growth, at least in the mitochondria-rich type I fibers (Kraemer et al., 1995; Putman et al., 2004).

Previous studies have shown that training can substantially improve the size and function of aging muscle, measured as strength or power (Jozsi et al., 1999; Häkkinen et al., 2001). However, some studies have found smaller adaptations in older compared with young adults (Welle et al., 1996; Kosek et al., 2006), possibly due to a decreased rate of muscle recovery (Kosek et al., 2006) or lower levels of anabolic hormones (Izquierdo et al., 2001). Therefore, information from younger subjects may not be directly applicable to older subjects. In older adults, previous studies have shown that low-frequency combined training (twice a week) (Izquierdo et al., 2004) and short-term (12-week) training (Wood et al., 2001) do not interfere with strength gains. This study aimed to clarify the possible interference effects of combining two strength and two endurance training sessions per week on neuromuscular performance and skeletal muscle fiber hypertrophy in previously untrained 40–67-year-old men during a prolonged (21 weeks) training program. It was hypothesized that prolonged high-intensity training combining strength and endurance modalities may interfere with strength development and muscle hypertrophy in aging men.

Methods

Subjects

Healthy untrained men ($n = 105$) aged 40–67 [mean 56 (standard deviation [SD] 7) years] were recruited for the study by advertising in newspapers and through e-mail lists. The participants were informed about the design of the study and the possible risks and discomforts related to the measurements, and all participants signed an informed consent. In all subjects, general

health status and resting electrocardiogram (ECG) were examined by a physician. In addition, the subjects who passed the medical examination performed a maximal exercise test to voluntary exhaustion with ECG monitoring under the supervision of a physician. Subjects showing signs of cardiovascular or musculo-skeletal problems were excluded from the study. The study plan was approved by the Ethics Committee of the University of Jyväskylä. The characteristics of the subjects before the training period are presented in Table 1.

Experimental design

The subjects were randomized into a strength training (S), endurance training (E), combined strength and endurance training (SE) or a control group (C). A total of 96 subjects completed the study: 25 subjects in S, 25 in E, 30 in SE and 16 in C. Nine of the original 105 subjects dropped out for different reasons, such as musculo-skeletal injuries, cardiac problems, delayed post-measurements due to a respiratory track infection or personal reasons. The measurements were performed once (aerobic performance and muscle biopsies) or twice (strength measurements and hormonal analysis) before the training, representing a control period of 2 weeks (–2) and in the middle of (at week 10) and after the 21-week training period. This study was part of a larger project, and the data on body composition and health-related physical performance have previously been published with a smaller number of subjects (Sillanpää et al., 2008).

Aerobic performance test

A graded maximal aerobic cycling test to volitional exhaustion was performed on a mechanically braked bicycle ergometer (Ergomedic 839E, Monark Exercise AB, Sweden) with simultaneous ECG and blood pressure monitoring. The test was supervised by a physician. The exercise intensity was increased by 20 W every 2 min starting with 50 W, and pedalling frequency was sustained at 60 r.p.m. throughout the test. Oxygen uptake (VO_2), carbon dioxide production (VCO_2), ventilation (VE), breathing frequency (Fr) and other standard respiratory parameters were measured continuously breath by breath (SensorMedics® Vmax229, SensorMedics Corporation, Yorba Linda, California, USA). VO_2 peak was determined as the highest minute average of VO_2 during the test (Mikkola et al., 2007). Maximal aerobic cycling power (P_{max}) was calculated with the following formula: $P_{\text{max}} = P_{\text{com}} + t/120\Delta P$, where P_{com} is the last cycling power completed, t is the time in seconds the non-completed power was maintained and ΔP is the increment in watts (Kuipers et al., 1985).

Strength and power measurements and recording of electromyography (EMG)

Concentric bilateral leg extension strength (hip, knee and ankle extensor strength) based on one repetition maximum

Table 1. Mean (SD) age, body height and weight, body mass index (BMI), peak oxygen uptake ($\text{VO}_{2\text{peak}}$), and one repetition maximum (1 RM) of bilateral leg extension in the strength training (S), endurance training (E), combined training (SE) and control (C) groups before the training period

	S ($n = 25$)	E ($n = 25$)	SE ($n = 30$)	C ($n = 16$)
Age (years)	56 (6)	54 (8)	56 (7)	55 (8)
Height (cm)	178 (6)	176 (6)	177 (8)	176 (6)
Weight (kg)	84 (8)	79 (10)	82 (13)	78 (6)
BMI (kg m^{-2})	26.4 (2.9)	25.5 (3.4)	26.2 (3.2)	25.3 (1.5)
$\text{VO}_{2\text{peak}}$ ($\text{mL kg}^{-1} \text{min}^{-1}$)	33.2 (6.4)	32.9 (7.2)	32.5 (4.2)	34.8 (5.5)
1 RM (kg)	166 (32)	154 (34)	158 (29)	153 (20)

(1 RM) in a horizontal leg press was measured on a David 210 dynamometer (David Fitness and Medical Ltd., Outokumpu, Finland) (Häkkinen et al., 1998a). The test was performed in a seated position with a hip angle of 110°. Subjects performed leg extension from 70° of knee flexion to full extension (180°). The load was increased for each trial until the subject failed to fully extend the knees. The load of the last successful performance was determined as 1 RM, which was usually achieved within three to five trials. Maximal concentric power was measured with a load of 50% of 1 RM using a dynamic explosive leg press exercise on a David 210 dynamometer. After baseline measurements, the load of the explosive leg press exercise was modified according to the changed 1 RM value after 10 and 21 weeks of training, in order to maintain the same relative load compared with baseline.

Isometric bilateral leg extension force was measured on a dynamometer (Häkkinen et al., 1998a) in a seated position with a knee angle of 107° and a hip angle of 110°. Subjects were instructed to generate maximum force as rapidly as possible against the force plate for a duration of 2–4 s. Isometric bench press was performed in a seated position with hip and knee angles of 90° (Häkkinen et al., 1998b). Maximal force was exerted against horizontal bars with the upper arm in a horizontal position and an elbow angle of 90°. For both exercises, subjects performed a minimum of three trials, and the trial with the highest peak force was selected for further analysis. The force signal was low pass filtered (20 Hz) and analyzed (Signal software Version 2.15, Cambridge Electronic Design Ltd., Cambridge, UK).

During the isometric bilateral leg extension, EMG was recorded from the vastus lateralis (VL) and vastus medialis (VM) of the right leg, and from the triceps brachii (TB) muscle during the isometric bench press. The skin was carefully prepared, and the bipolar surface electrodes were placed according to SENIAM guidelines (Hermens et al., 1999) (inter-electrode distance 20 mm and resistance <10 k Ω). The signal was recorded telemetrically (Telemetry 2400R, Noraxon, Scottsdale, Arizona, USA), amplified with a factor of 500, band pass filtered (20–350 Hz), digitized at a sampling frequency of 2000 Hz (Micro1401, CED, Cambridge, UK) and analyzed (Signal software Version 2.15, Cambridge Electronic Design Ltd.). Maximum iEMG was calculated for the maximal force phase of the isometric contractions (500–1500 ms) (Häkkinen et al., 1998a). To ensure repeatable measurements throughout the study period, small ink tattoos were used to mark the positions of the electrodes on the skin (Häkkinen et al., 1998a).

Muscle biopsies

It was only possible to obtain muscle biopsies from 11 subjects in S, seven in E, 12 in SE and three in C before and after the 21-week training period. Biopsies were taken from the VL muscle, midway between the patella and greater trochanter using the percutaneous needle biopsy technique (Bergström & Hultman, 1966). After the training period, muscle biopsies were carefully obtained from the same depth, 0.5 cm lateral to the preceding biopsy. The samples were mounted on a cork and frozen immediately in isopentane (–160 °C) and stored at –80 °C. For histochemical analysis, serial cross-sections (8 μ m thick) were cut on a cryomicrotome (Leica CM 3000), Leica Microsystems, Wetzlar, Germany at –24 °C and stained with a myofibrillar ATPase method after preincubation at a pH of 4.37, 4.60 and 10.30 to define four different fiber types (Types I, IIA, IIX and IIX) (Ennion et al., 1995). The stained cross-sections were analyzed using a microscope (Olympus BX50, Olympus Optical Co., Tokyo, Japan) and a color video camera (Sanyo high-resolution CCD, Sanyo Electronic Co., Osaka,

Japan) combined with image-analysis software (Tema, Scan Beam, Hadsund, Denmark). Fiber type distribution and CSA were determined from a mean fiber number of 147 (SD 43) and 137 (46) in S, 145 (54) and 157 (30) in E, 142 (65) and 165 (52) in SE and 149 (41) and 132 (30) in C, at the pre- and post-training intervals, respectively.

Blood samples

Fasting blood samples were obtained from the antecubital vein in the morning, to enable the determination of basal serum total testosterone and cortisol concentrations. The blood was centrifuged, and serum samples were kept frozen at –80 °C until analysis. Serum total testosterone concentrations were analyzed in duplicate using an immunological chemiluminescence method using a Bayer ADVIA Centaur analyzer (Tarrytown, New York, USA), and cortisol concentrations were determined by radioimmunoassay (Farnos Diagnostica, Turku, Finland). For each hormone, all serum samples of each subject were analyzed in the same assay. Assay sensitivity values were 0.6 nmol/L and 0.006 μ mol/L for testosterone and cortisol, respectively. The intra-assay coefficient of variation was 5.7% for testosterone and 4.0% for cortisol. Basal hormone concentrations are only reported for subjects in whom fiber type distribution and CSA data were also obtained.

Strength training

Strength training was carried out twice a week. All strength training sessions were supervised. The strength training program included seven to 10 exercises that activated all of the main muscle groups. Every training session included two exercises for the leg extensors (leg press and knee extension), one exercise for knee flexors (leg curl) and one to two other exercises for the lower extremities (seated calf raise, hip abduction or adduction). For the upper body, each session included three to four exercises (bench press, biceps curl, triceps push-down, lateral pull-down), and one to two exercises for the trunk (abdominal crunch, seated back extension). The overall intensity and amount of training increased progressively throughout the 21-week training period (Häkkinen et al., 1998a).

The training period was divided into three 7-week cycles to optimize strength gains and muscle hypertrophy. The focus of the first cycle was to accustom the subjects to the high-intensity training and to improve muscle strength and muscle endurance using light loads (40–60% of 1 RM) and a high number (12–20) of repetitions, and by performing three sets. The second cycle (weeks 8–14) was designed to produce muscle hypertrophy to further increase the total muscle mass/fat ratio by increasing the loads progressively up to 60–80% of the maximum, with 5–12 repetitions and two to four sets. To optimize strength development and to further produce hypertrophy during weeks 15–21, higher loads of 70–85% of 1 RM together with five to eight repetitions and two to four sets were used. In addition, approximately 20% of the leg press, knee extension and bench press exercises were performed with light loads of 40–50% of 1 RM and five to eight repetitions, to meet the requirements of a typical explosive strength training protocol. With the light loads, each repetition was executed as rapidly as possible (Häkkinen et al., 1998a).

Endurance training

Endurance training was carried out twice a week. The heart rate levels for endurance training were determined based on respiratory parameters and blood lactate concentrations, as described in detail previously (Aunola & Rusko, 1984). All

training sessions were supervised, and heart rate monitoring was used. During the first 7-week period, the subjects trained on a bicycle ergometer for 30 min below the level of the aerobic threshold. Weeks 5–7 during the first period also included three training sessions during which the subjects were accustomed to the intensity above the aerobic threshold by a 10-min interval in the middle of the sessions. During weeks 8–14, one weekly session of 45 min included a 10-min interval between the aerobic–anaerobic thresholds and a 5-min interval above the anaerobic threshold, in addition to a 15-min warm-up and a 15-min cooldown below the aerobic threshold. The other weekly training session involved 60 min of cycling below the aerobic threshold. The focus of training during weeks 15–21 was to improve maximal endurance. One of the weekly sessions lasted for 60 min, which included two 10-min intervals between the aerobic–anaerobic thresholds, two 5-min intervals above the anaerobic threshold and 30 min below the aerobic threshold. The other weekly session included 90 min of cycling at a steady pace below the aerobic threshold.

Combined endurance and strength training

The subjects in the combined group performed endurance training twice a week and strength training twice a week, performing a total of four training sessions per week as described in the preceding paragraphs (Häkkinen et al., 2003).

Statistical analyses

The results are expressed as means and SD. Training effects and differences between the groups were studied using analysis of variance (ANOVA) with repeated measures and one-way ANOVA for relative changes at post-training measurement. The assumptions for repeated measures ANOVA, homogeneity of variance, sphericity and normal distribution were tested. If the assumptions were not met, even after a natural log transformation, an analogous nonparametric test was used. Bonferroni's correction was used for further comparisons between time points within each group. The critical level of significance was set at $P = 0.05$. The statistical analyses were carried out using SPSS 14.0 software for Windows (SPSS Inc., Chicago, Illinois, USA).

Results

Muscle strength, power and activation

No significant changes were observed in isometric or dynamic strength, concentric power or muscle activation in any of the groups during the control period. After 21 weeks of training, maximal isometric force of the lower extremities increased by 20 (15)% in SE and by 14 (11)% in S, whereas in E only by 9 (12)% and in C by 6 (9)% [Fig. 1(a)]. The corresponding changes in bilateral leg press 1 RM were 22 (9)%, 21 (8)%, 7 (5)% and 5 (4)% in SE, S, E and C, respectively [Fig. 2(a)]. Maximal isometric force of the upper extremities increased by 14 (11)% in SE, 12 (11)% in S, 6 (9)% in E, but was unchanged in C [1 (7)%] [Fig. 1(b)]. There was a significant between-group difference over time ($P < 0.001$) in all of these variables, as well as in maximal concentric power of the lower extremities ($P = 0.020$), which increased in S by 16 (22)% ($P = 0.022$) and in SE by 16 (31)% ($P = 0.024$) [Fig. 2(b)], but not in E [– 6 (25)%] or C [1 (14)%].

During maximal isometric leg press, the EMG activity of VM increased significantly more in SE and S than E or C ($P = 0.042$) during the 21-week training period. EMG activity of VL increased in S and C, but with no significant difference between groups. In both S and SE, muscle activation increased in VM by 41 (47)% and 18 (28)% [Fig. 3(a)], and in VL by 35 (49)% and 11 (18)%, respectively, between training weeks 0 and 10, whereas between weeks 10 and 21, there was no further increase [Fig. 3(a)]. Therefore, the statistics for EMG of VM and VL were also calculated with one-way ANOVA for the relative changes at week 10 between S, SE and E. There was a significant difference between groups ($P < 0.01$), whereby the increase in muscle activation of VM and VL in S was larger than in SE or E at week 10. Muscle activation of TB seemed to increase throughout the

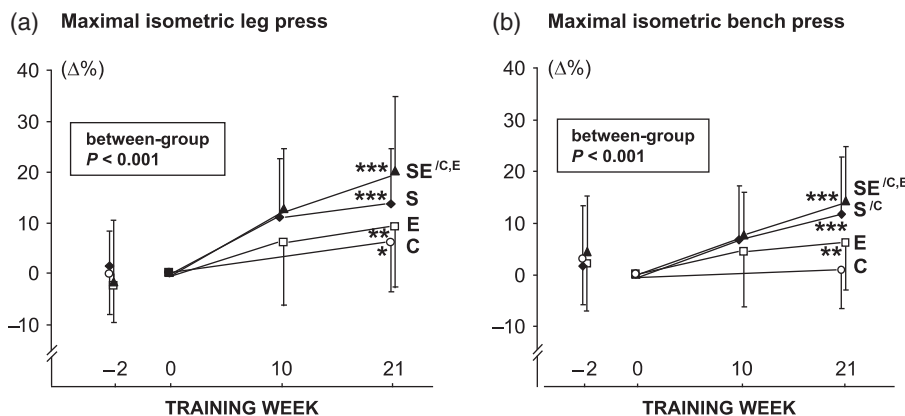


Fig. 1. Changes (%) in the maximal isometric force of (a) lower and (b) upper extremity extensors during the control period (– 2 and 0 weeks), and after 10 and 21 weeks of strength (S), endurance (E) or combined strength and endurance (SE) training, and in the control group (C). *Significantly ($P < 0.05$) different from the baseline measurement, ** $P < 0.01$, *** $P < 0.001$. Significant differences between the groups at week 21 are indicated with superscripts, for example, ^{SE/C,E} Significantly different from the C and E groups.

Combined endurance and strength training

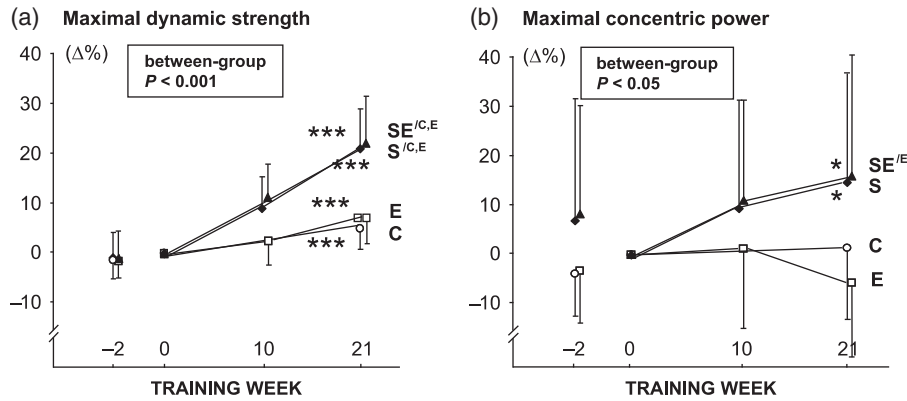


Fig. 2. Changes (%) in (a) the maximal dynamic strength of lower extremity extensors in leg press (one repetition maximum) and (b) the maximal concentric leg extension power during the control period (–2 and 0 weeks), and after 10 and 21 weeks of strength (S), endurance (E) or combined strength and endurance (SE) training and in the control group (C). *Significantly ($P < 0.05$) different from the baseline measurement, *** $P < 0.001$. Significant differences between the groups at week 21 are indicated with superscripts, ^{/C,E}Significantly different from the C and E groups.

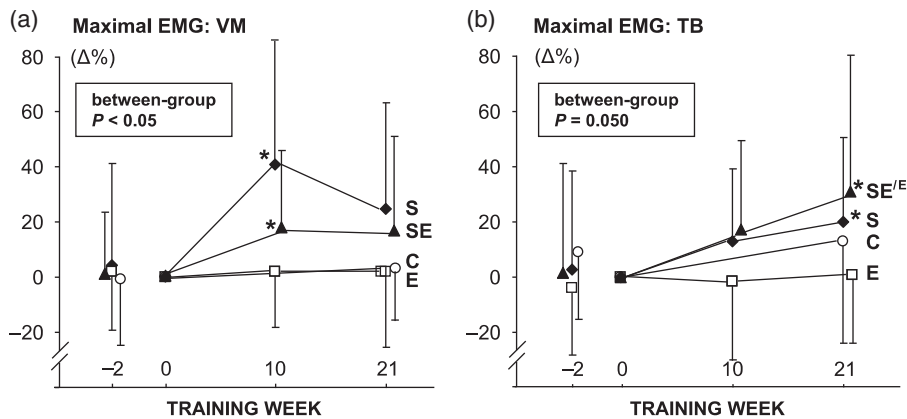


Fig. 3. Maximal electromyographic (EMG) activity in (a) vastus medialis (VM) and (b) triceps brachii (TB) muscles during maximal isometric leg extension of lower and upper extremities, respectively, during the control period (–2 and 0 weeks), and after 10 and 21 weeks of strength (S), endurance (E) or combined strength and endurance (SE) training and in the control group (C). *Significantly ($P < 0.05$) different from the baseline measurement. Significant differences between the groups at week 21 are indicated with superscripts, ^{/E}Significantly different from the E group.

training period in SE and S ($P < 0.05$), and the change was not significant in any other group [Fig. 3(b)].

Aerobic performance

During the 21-week training period, VO_2 peak increased in SE and E by 10 (10)% and 12 (11)% ($P < 0.001$), respectively, but did not change in S [0 (10)%] or C [0 (8)%] [Fig. 4(a)]. After 10 weeks of training, the increase in VO_2 peak was 5 (8)% and 7 (9)% in SE and E, respectively. There was no difference between SE and E in the improvement of VO_2 peak. P_{max} increased in all training groups: 13 (7)% in SE, 14 (9)% in E, and 6 (6)% in S, but not in C [–2 (5)%] [Fig. 4(b)].

Muscle fiber size and distribution

When all three subtypes of type II fibers were combined in the analysis, the cross-sectional area

(CSA) of type II fibers increased in S, without significant changes in any other groups (Fig. 5). The change in CSA of type IIA muscle fibers was also significant ($P = 0.050$) in S, with a 16 (24)% increase, and did not change in the other groups. In S, the proportion of type IIA fibers increased from 36 (20)% to 50 (12)% ($P = 0.031$), and type IIXA decreased from 18 (12)% to 5 (6)% ($P = 0.003$) (Table 2). No changes were observed in the CSA or the proportion of type I fibers in any of the groups (Fig. 5, Table 2).

Hormone concentrations

Basal concentrations of testosterone and cortisol did not change significantly in any of the groups during the control period (Table 3). No significant training-induced changes were observed in the resting concentrations of testosterone or cortisol, although S

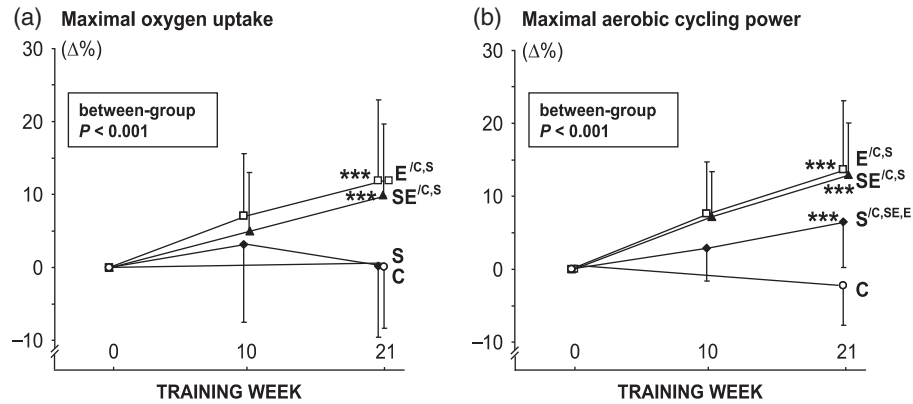


Fig. 4. Changes (%) in (a) maximal oxygen uptake and (b) maximal aerobic cycling power before (0) and after 10 and 21 weeks of strength (S), endurance (E) or combined strength and endurance (SE) training and in the control group (C). ***Significantly ($P < 0.001$) different from the baseline measurement. Significant differences between the groups at week 21 are indicated with superscripts, for example, ^{E/C,S} Significantly different from the C, SE and S groups.

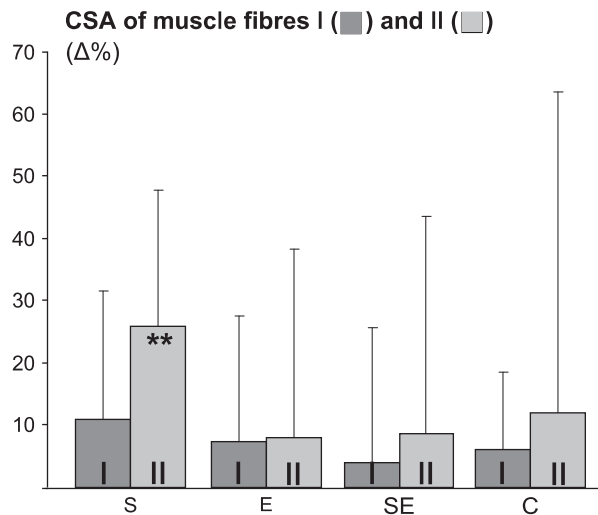


Fig. 5. Changes (%) in the mean cross-sectional area (CSA) of type I and II muscle fibers in vastus lateralis muscle before (0) and after 21 weeks of strength (S), endurance (E), combined strength and endurance (SE) training or a control (C) period. **Significantly ($P < 0.01$) different from the baseline measurement.

showed an increasing trend ($P = 0.084$) in the concentration of testosterone. In S, the concentration of testosterone after 10 and 21 weeks of training correlated significantly with the changes in CSA of type IIA fibers ($r = 0.69$, $P = 0.020$ and $r = 0.76$, $P = 0.006$).

Discussion

The present study examined the effects of combined progressive endurance and strength training in previously untrained 40–67-year-old men. The primary aim was to investigate the potential interference effect of high-intensity combined training on strength gains and muscle hypertrophy over a prolonged training

period of 21 weeks. The results suggest that combined training with a total of 4 training sessions per week leads to significant gains in maximal strength that are as large as with strength training alone. However, the CSA of type II muscle fibers only increased with strength training, but not with combined training. This observation implies that muscle hypertrophy might be compromised when combining the two different training modes, despite the similar strength gains in the S and SE groups.

The diversity of possible training programs comprised of training design variables such as volume, frequency, duration and intensity raises some controversy in the literature about the universal nature of interference effects (Leveritt et al., 1999). The similar development of neuromuscular performance in the strength and combined groups in the present study supports previous observations in younger adults (Sale et al., 1990; McCarthy et al., 2002; Häkkinen et al., 2003), suggesting that with a moderate volume and/or frequency, concurrent training does not counteract strength gains. Therefore, the results of our study, together with a previous investigation (Izquierdo et al., 2004) with one weekly strength and one endurance training session, suggest that this also applies to older men. The present finding is also in line with an earlier study in somewhat older subjects (Wood et al., 2001), which observed no interference from 12 weeks of endurance and strength training performed three times a week on the same day, although with a somewhat lower training intensity in the present study. The present study showed, therefore, that combined training on separate days can be continued even for 21 weeks without compromising the strength gains.

Two sessions per week of endurance or strength training alone led to predictable specific improve-

Table 2. Group mean (SD) muscle fiber type distribution before (pre) and after (post) 21 weeks of strength (S), endurance (E) or combined strength and endurance (SE) training and in the control group (C)

	S (n = 11)		E (n = 7)		SE (n = 12)		C (n = 3)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Type I (%)	40 (18)	45 (13)	44 (15)	48 (17)	45 (6)	42 (14)	46 (10)	55 (6)
Type IIA (%)	36 (20)	50 (12)*	35 (13)	41 (14)	41 (8)	49 (14)	23 (3)	22 (7)
Type IIX (%)	18 (12)	5 (6)**	14 (4)	9 (7)	13 (8)	6 (10)	31 (7)	20 (7)
Type IIX (%)	6 (9)	0.2 (0.4)	7 (5)	2 (4)	1 (1)	3 (7)	0.5 (0.5)	3 (4)

*Significantly ($P < 0.05$) different from the baseline measurement.

** $P < 0.01$.

Table 3. Mean (SD) basal hormone concentrations for the endurance (E), strength (S), combined strength and endurance training (SE) and control (C) groups

	- 2	0	10	21
Testosterone (nmol/L)				
S (n = 11)	14.3 (2.5)	14.7 (3.7)	16.4 (5.4)	16.4 (4.3)
E (n = 6)	19.9 (6.0)	17.8 (4.4)	18.4 (5.4)	19.3 (3.6)
SE (n = 12)	16.3 (4.5)	19.1 (7.4)	19.8 (6.7)	19.9 (6.5)
C (n = 3)	20.9 (2.5)	18.5 (6.0)		18.1 (10.6)
Cortisol (µmol/L)				
S (n = 11)	0.39 (0.06)	0.43 (0.12)	0.44 (0.11)	0.42 (0.08)
E (n = 6)	0.49 (0.14)	0.46 (0.05)	0.51 (0.10)	0.51 (0.14)
SE (n = 12)	0.49 (0.10)	0.49 (0.12)	0.47 (0.11)	0.47 (0.10)
C (n = 3)	0.36 (0.09)	0.46 (0.10)		0.39 (0.06)

ments in either strength or endurance performance. The relative changes in maximal force of the lower (14% and 20% in S and SE, respectively) and upper (12% and 14%) extremities were somewhat smaller than in previous studies with a similar training program in older men (Häkkinen et al., 1998a). The changes in VO_2 peak, 12% and 10% in E and SE, were also slightly smaller than those observed previously in middle-aged men (Häkkinen et al., 2003). However, within the present study group, there were no significant correlations between age and training response in any of the variables. In the present training program, approximately 20% of the volume of strength training for the lower extremities was performed explosively. Accordingly, both S and SE training led to improvements in maximal concentric power of the leg extensors. A non-significant decrease in concentric power was observed in E between training weeks 10 and 21, although it is possible that a longer endurance training period would have induced a significant decrease.

CSA of the type IIA fibers and the mean area of all type II fibers increased in S by 16% and 26%, respectively, after 21 weeks of progressive strength training two times a week. Similar or somewhat smaller gains have been reported previously in older men with two to three strength training sessions per week (Häkkinen et al., 2001; Martel et al., 2006).

Interestingly, no increases in the CSA of any of the fiber types were observed with the present prolonged strength training program when combined with two weekly sessions of endurance training, including cycling with a high intensity. Even though the difference between the SE and S groups was not significant, the large interindividual variation in SE suggests diverse adaptations in muscle hypertrophy, compared with a systematic increase in S (Fig. 5). It should be noted that interference in hypertrophy was observed in one half of the subjects in SE, whereas the other half were able to increase their fiber size. This finding is also supported by a previous observation in a sample of the same male population, as the increase in the lean mass of the legs was only significantly increased in S (Sillanpää et al., 2008). In addition, combined training has previously been reported to interfere with muscle hypertrophy in young adults, although mainly with regard to type I fibers (Kraemer et al., 1995; Bell et al., 2000; McCarthy et al., 2002).

In the study by Kraemer et al. (1995), strength training alone increased the CSA of type I fibers, and endurance training alone seemed to decrease CSA, whereas combined training induced no change, thus demonstrating an intermediate response. Two other studies have observed a significant change in CSA of type I fibers with strength training, no change with endurance training and no change with combined training (Bell et al., 2000; McCarthy et al., 2002). In older adults, however, type I fibers do not seem to show as large strength training-induced increases in CSA as those in young adults (Charette et al., 1991; Martel et al., 2006; Kryger & Andersen, 2007). Besides the older age of the present subjects, the current strength training program could explain why the interference effect was found in the type II fibers, without significant increases in the type I fibers. In the present study, approximately 20% of the volume of strength training for the leg extensors was performed using a typical explosive strength training protocol with lower loads and a short duration of each repetition. In addition, during the first 7 weeks, strength training was performed with relatively low loads that are not likely to produce major hypertrophy. The incompat-

ibility of endurance and strength training in type II fibers observed in the present study is especially important in older adults, because type II fibers have a greater potential for muscle growth and a higher force per unit area than type I fibers (Harridge, 2007).

A few possible mechanisms for the interference of muscle hypertrophy with combined endurance and strength training have been proposed that are related to the different signaling pathways of these two training modes (Baar, 2006; Nader, 2006). Another possible factor leading to interference could be the greater potential of aerobic exercise compared with strength exercise to induce oxidative stress due to the duration-dependent nature of free radical production. Many biologically important substances involved in muscle hypertrophy, such as nucleic acid and protein, are at a theoretical risk to cellular damage (Pattwell & Jackson, 2004; Fisher-Wellman & Bloomer, 2009). Combined training has also been suggested to lead to a catabolic state, as evidenced by increased cortisol levels in younger men (Kraemer et al., 1995; Bell et al., 1997). However, the present data with older subjects showed no significant changes in the basal hormone concentrations of cortisol during the 21-week training period. A significant positive correlation between testosterone concentration and changes in the CSA of type IIA fibers was only observed in S.

It should also be taken into account that using the same strength training program in both SE and S, as well as the same endurance training program in SE and E, causes a larger training volume in the combined group. Therefore, we cannot exclude overtraining or overreaching as a possible mechanism for the interference in muscle hypertrophy (Leveritt et al., 1999). However, impaired performance is often considered as a marker of overtraining, but in our study the strength increased similarly in S and SE. In addition, interference in strength gains has also been detected with a very low training volume that is not likely to cause overtraining (Dudley & Djamil, 1985). Even though the subjects from whom the biopsies were obtained showed similar adaptation compared with the total training groups, the present muscle fiber data should be interpreted with some caution. The number of subjects was small compared with the total sample size. Furthermore, muscle fiber size was only measured in the VL muscle, whereas the leg press exercise used in the present study activates several muscles of the knee, hip and ankle extensors.

In both the strength and the combined training groups, improvements in strength were associated with enhanced muscle activation. It has been suggested that when interference is observed in muscle hypertrophy, strength gains may be maintained by neural mechanisms (Leveritt et al., 1999). This seems

not to be the case in the present study, however, because at training week 10, the S group showed a larger increase in muscle activation in VL and VM than the SE group. However, no significant differences were found between groups after 21 weeks of training. As we have no data on muscle hypertrophy at training week 10, it is not appropriate to make comparisons between muscular and neural adaptations. EMG was recorded from the VL and VM muscles during isometric leg extension. It should be noted therefore that the recording of EMG in only two leg extensor muscles may not be sensitive enough to detect changes in neural activation of both agonistic and synergistic, and especially antagonistic muscles in a multi-joint exercise.

Perspectives

Both strength and endurance training have several positive effects on aging muscle and the physical performance of middle-aged and older adults. Based on previous studies in young subjects, the combination of these two different training modes may interfere with optimal neuromuscular adaptation, depending on the training intensity, frequency and duration. However, information from younger subjects may not be directly applicable to older subjects. The present results show that combined strength and endurance training for 21 weeks in previously untrained 40–67-year-old men improves strength performance to the same extent as strength training alone when both strength and endurance training modes are performed twice a week. When combined, strength and endurance training for a total of four sessions per week did not compromise the improvements in maximal strength, concentric power or aerobic capacity. However, the changes in muscle fiber size found only in the strength-trained group may indicate diminished muscle hypertrophy when strength and endurance training are combined over a prolonged period. Therefore, when designing combined training programs for middle-aged and older adults to prevent or delay the age-related loss of skeletal muscle mass, the possible interference of muscular adaptation, particularly in type II fibers, should be taken into account.

Key words: neuromuscular adaptation, aging, muscle fiber size.

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Karavirta et al.

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