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ORIGINAL ARTICLE

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Neuromuscular adaptations during concurrent strength and endurance training versus strength training

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Abstract The purpose of this study was to investigate effects of concurrent strength and endurance training (SE) (2 plus 2 days a week) versus strength training only (S) (2 days a week) in men [SE: $n = 11$; 38 (5) years, S: $n = 16$; 37 (5) years] over a training period of 21 weeks. The resistance training program addressed both maximal and explosive strength components. EMG, maximal isometric force, 1 RM strength, and rate of force development (RFD) of the leg extensors, muscle cross-sectional area (CSA) of the quadriceps femoris (QF) throughout the lengths of 4/15–12/15 (L_f) of the femur, muscle fibre proportion and areas of types I, IIa, and IIb of the vastus lateralis (VL), and maximal oxygen uptake ($\dot{V}O_{2max}$) were evaluated. No changes occurred in strength during the 1-week control period, while after the 21-week training period increases of 21% ($p < 0.001$) and 22% ($p < 0.001$), and of 22% ($p < 0.001$) and 21% ($p < 0.001$) took place in the 1RM load and maximal isometric force in S and SE, respectively. Increases of 26% ($p < 0.05$) and 29% ($p < 0.001$) occurred in the maximum iEMG of the VL in S and SE, respectively. The CSA of the QF increased throughout the length of the QF (from 4/15 to 12/15 L_f) both in S ($p < 0.05$–0.001) and SE ($p < 0.01$–0.001). The mean fibre areas of types I, IIa and IIb increased after the training both in S ($p < 0.05$ and 0.01) and SE ($p < 0.05$ and $p < 0.01$). S showed an increase in RFD ($p < 0.01$), while no change occurred in SE. The average iEMG of the VL during the first 500 ms of the rapid isometric action increased ($p < 0.05$–0.001) only in S. $\dot{V}O_{2max}$ increased by 18.5% ($p < 0.001$) in SE. The present data do not support the concept of the universal nature of the interference effect in strength development and muscle hypertrophy when strength training is performed concurrently with endurance training, and the training volume is diluted by a longer period of time with a low frequency of training. However, the present results suggest that even the low-frequency concurrent strength and endurance training leads to interference in explosive strength development mediated in part by the limitations of rapid voluntary neural activation of the trained muscles.

Keywords Hypertrophy · Neural activation · Power · Strength · Strength vs. endurance training

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Introduction

The specificity of training has been well documented, so that prolonged endurance training enhances aerobic performance by improving maximal oxygen uptake ($\dot{V}O_{2max}$, oxidative capacity) and increasing muscle aerobic enzyme activities, intramuscular glycogen stores, and capillary and mitochondrial density of the muscles (Holloszy and

Coyle 1984; Åstrand and Rodahl 1986). On the other hand, typical strength training with high loads results in neural and muscle hypertrophic adaptations responsible for improved strength of the trained muscles (Komi 1986; McDougall 1992; Sale 1992; Häkkinen 1994).

The physiological stimuli directed to skeletal muscle as a result of strength training and endurance training are divergent in nature. Actually, it has been suggested that they may even be antagonist to gains in strength (Hickson 1980; Dudley and Djamil 1985; Hunter et al. 1987; Hortobagyi et al. 1991; Kraemer et al. 1995; Bell et al. 1991, 2000). Under these concurrent training conditions, there would be a limited change in skeletal muscle cross-sectional area (CSA, Bell et al. 1991) and/or a reduced hypertrophy of individual muscle fibres (Kraemer et al 1995; Bell et al. 2000). More specifically, Kraemer et al. (1995) demonstrated that combined training muted the hypertrophy of type I fibres. However, concurrent training may not impair adaptations in strength, muscle hypertrophy, and neural activation induced by strength training only over a short-term period (McCarthy et al. 2002). To the best of our knowledge no data have yet been reported on neural activation of trained muscles as a result of prolonged combined strength and endurance training. The training-induced adaptations in the neuromuscular system differ according to the specific mode of exercise used for strength training. For example, between maximal strength training regimens versus explosive strength training protocols (Häkkinen et al 1985a, 1985b), this compatibility may be different between endurance training and strength training depending upon the types of strength training utilized. Thus, the degree of the antagonism that occurs as a result of combined strength and endurance training may differ based on the nature of the resistance training program and the target goal (e.g. power versus 1RM strength).

Nevertheless, most studies seem to support the contention that the adaptation to typical strength training is different when combined with endurance training. In addition, the volume and frequency of training may also influence the amount of incompatibility observed. Recently, McCarthy et al. (1995) demonstrated no incompatibility when combined training was only performed 3 days per week. Thus, training frequency and the intensity of each program may influence the level of interference. The physiological basis for this may be linked to an interaction between an elevated catabolic hormonal state leading to a reduced change in skeletal muscle CSA (Kraemer et al. 1995; Bell et al. 2000).

Conversely, other studies have shown a synergistic or additive effect in some muscle adaptations (Sale et al. 1990), or a compatibility in certain adaptations as a result of concurrent strength and endurance training (McCarthy et al. 1995). The compatibility may also have an overtraining aspect to it as well, and untrained individuals may be more susceptible to stress than trained people. Thus, some controversies exist regarding the universal nature the "interference effect" that was initially described by Hickson (1980). Nevertheless, this interference effect may hold true when the overall volume of training is high, so that simultaneous training for both strength and endurance may be associated with large strength gains during the initial weeks of training but with only limited strength development later on.

The training for physical fitness of ordinary people and, for example, the military forces calls for the development of muscle strength and endurance but the requirements for the volume and/or frequency of training in ordinary people are usually lower than in training of athletes for some sports. Therefore, the purpose of this study was to investigate the effects of combined strength and endurance training versus those of strength training alone on both functional and structural adaptations of the neuromuscular system in men during a prolonged training period of 21 weeks, while keeping the overall frequency of training at a low level throughout the experiment. Moreover, the subject groups utilized a strength training program planned not only for maximal strength development but also included to some extent lower-load exercises of an explosive nature, i.e. to execute each repetition of these sets as "explosively" as possible (rapid muscle actions). The focus of this study was on the neuromuscular system, thus we recorded the degree of hypertrophic adaptation and maximal strength development of the trained muscles. We were also interested in examining possible training-induced adaptations in voluntary neural activation of the trained muscles possibly associated with power development.

Methods

Subjects

Thirty-two healthy men from the city of Jyväskylä were recruited for the study. Five subjects dropped out after the first measurements or later during the study period (for various personal reasons) so that in the end 16 subjects [mean age of 38 (5) years and mean height of 179 (5) cm] were left in the strength training (S) group and 11 subjects [37 (5) years and 181 (8) cm] were in the combined strength and endurance training (SE) group. The physical characteristics of the subject groups are presented in Table 1. The subjects were carefully informed about the design of the study with special information on possible risks and discomfort that might result, and subsequently signed an informed consent document prior to the start of the study. The study was conducted according to the declaration of Helsinki and was approved by the Ethics Committee of the University of Jyväskylä, Finland.

Subjects had been previously involved with various recreational physical activities such as walking, jogging, cross-country skiing, aerobics or biking but none of the subjects had any background in regular strength training or competitive sports of any kind. Subjects were not on any medications that would affect physical performance.

Experimental design

The total duration of the present study was 22 weeks. The subjects were tested on five different occasions using identical protocols. The first week of the study (between the measurements at week –1 and at 0) was used as a control period during which time no experimental training was carried out but the subjects maintained

Table 1 Physical characteristics of the subject groups during the experimental period

Weeks	Strength group (S) ($n=16$)				Strength endurance group (SE) ($n=11$)			
	Mass (kg)		Body fat %		Mass (kg)		Body fat %	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0	83.9	(15.0)	20.1	(4.9)	88.6	(12.9)	22.5	(4.5)
7	84.6	(15.8)	20.3	(4.9)	88.2	(11.9)	21.6*	(4.5)
14	85.1	(16.3)	20.6	(5.2)	88.1	(11.9)	21.3***	(4.5)
21	85.9	(18.1)	20.4	(5.3)	87.3	(11.5)	20.2***	(4.4)

*$p<0.05$; ***$p<0.001$

their normal recreational physical activities (e.g. walking, jogging, biking, swimming and aerobics). These activities were similar between the groups. The subjects were tested before and after this control period. Thereafter, the subjects started a supervised experimental training period for 21 weeks in the S or the SE group. The measurements were repeated during the actual experimental training period at 7-week intervals (i.e. weeks 0, 7, 14 and 21).

Muscle strength measurements

The subjects were carefully familiarized with the testing procedures of voluntary force production of the muscle groups tested. Second, during the actual testing occasion, two to three warm-up contractions were performed prior to the maximal test actions. In all tests of physical performance external verbal encouragement was given to each subject.

Isometric force–time curves, maximal rate of isometric force development (RFD), and maximal isometric force of the bilateral leg extensor muscles (hip, knee and ankle extensors) were measured on an electromechanical dynamometer (Häkkinen et al. 1998a). In this test the subjects were in a sitting position so that the knee and hip angles were 107° and 110°, respectively. The subjects were instructed to exert their maximal force as fast as possible during a period of 2.5–4.0 s. A minimum of three trials was completed for each subject and the best performance trial with regard to maximal peak force was used for the subsequent statistical analysis.

A David 210 dynamometer (David Fitness and Medical) was used to measure maximal bilateral concentric force production of the leg extensors (hip, knee and ankle extensors) (Häkkinen et al. 1998a). The subject was in a seated position so that the hip angle was 110°. On verbal command the subject performed a concentric leg extension starting from a flexed position of 70° trying to reach a full extension of 180° against the resistance determined by the loads (kg) chosen on the weight stack. In the testing of the maximal load, separate 1RM (repetition maximum) contractions were performed. After each repetition the load was increased until the subject was unable to extend the legs to the required full extension position. The last acceptable extension with the highest possible load was determined as 1RM. This dynamic testing action was used in addition to that of the isometric one, since the strength training was also dynamic in nature.

A David 200 dynamometer modified for strength testing (Häkkinen et al 1998b) was used to measure maximal isometric torque of the knee flexors. The subject was in a seated position so that the hip and knee angles were 110° and 90°, respectively. On verbal command the subject performed a maximum isometric knee flexion of the right leg. A minimum of two maximal actions was recorded and the best maximum was taken for further analysis.

The force signal was recorded on a computer (486 DX-100) and thereafter digitized and analysed with a Codas TM computer system (Data Instruments). Maximal peak force was defined as the highest value of the force (N) recorded during the bilateral isometric leg extension and unilateral (right) isometric knee flexion action (N). The force–CPôtime analysis on the absolute scale included the calculation of average force (N) produced during the first 500 ms from the start of the contraction (Häkkinen et al. 1998a). The maximal RFD ($N\cdot s^{-1}$) was also analysed and defined as the greatest increase in force in a given 50-ms time period (Häkkinen et al. 1998a).

EMG measurements

Electromyographic (EMG) activity during the bilateral and unilateral extension actions of the leg muscles was recorded from the agonist vastus lateralis (VL) of the right and left leg and from the antagonist muscle of biceps femoris (BF; long head) of the right leg separately. Bipolar (20 mm interelectrode distance) surface EMG recording (Beckman miniature-sized skin electrodes 650437, Illinois, USA) was employed. The electrodes were placed longitudinally on the motor point areas of the muscles examined, and EMG signals were recorded telemetrically (Glonner, Biomes 2000). The positions of the electrodes were marked on the skin by small ink tattoos (Häkkinen et al. 1998b). These dots ensured the same electrode positioning in each test over the 22-week experimental period. The EMG signal was amplified (by a multiplication factor of 200; low-pass cut-off frequency of 360 Hz 3 dB^{-1}) and digitized at a sampling frequency of 1000 Hz by an on-line computer system. EMG was full wave rectified, integrated (iEMG in mV·s) and time normalized for 1 s in the following phases: (1) in the isometric actions for the first 500 ms from the start of the contraction, and (2) for the maximal peak force phase of the isometric contractions (500–1500 ms) to calculate maximal iEMG (Häkkinen et al. 1998a). EMG of the BF acting as an agonist recorded during the maximal unilateral isometric knee flexion was analysed in a similar way as those of the EMGs of the VL muscles of the isometric leg extensions. The highest iEMG value recorded for the right BF muscle was taken for further analysis. The iEMG of the right BF acting as an antagonist was also recorded during the bilateral isometric leg extension action. In order to calculate the antagonist coactivation percentage for the BF muscle during the extension action, the following formula was used: iEMG of the BF during the extension divided by the iEMG of the BF during the flexion, all multiplied by 100) (Häkkinen et al. 1998a, 1998b).

Muscle CSA

The muscle CSA of the right quadriceps femoris (QF) was assessed before and after the 21-week experimental training using magnetic resonance imaging (MRI) (1.5-Tesla, Gyroscan S15, Philips) at Keski-Suomen Magneettikuvaus, Jyväskylä, Finland. The length of the femur (L_f), taken as the distance from the bottom of the lateral femoral condyle to the lower corner of the femoral head, was measured on the coronal plane. Subsequently, 15 axial scans of the thigh interspaced by a distance of 1/15 L_f were obtained from the level of 1/15 L_f to 15/15 L_f as described previously (Häkkinen et al. 2001b). Great care was taken to reproduce the same individual femur length each time using the appropriate anatomical landmarks. All MR images were then exported to a Macintosh computer for the calculation of muscle CSA. For each axial scan, CSA computation was carried out on the QF as a whole and for the final calculation of the CSA, slices 4/15–12/15 were used (slice 4 being closer to the knee joint of the thigh). CSA (measured in cm^2) was determined by tracing manually along the border of the QF.

Muscle biopsy samples were obtained before and after the experimental training period. The samples were obtained from the superficial portion of the VL muscle of the right leg utilizing the percutaneous needle biopsy technique of Bergström (1962). Special care was taken to extract tissue from the same location (close to the prebiopsy scar) and depth each time. Muscle tissue samples were frozen in isopentane cooled with liquid nitrogen and stored at –80°C until analysis. Serial cross-sections (10 μm thick) were cut on a cryostat at –20°C for histochemical analyses. Histochemical staining for myofibrillar adenosinetriphosphatase (ATPase) was used to classify the fibers as I, IIa, IIb and IIc (based on the stability of their ATPase activity at pH 4.2, 4.6, and 10.3. in the preincubation medium) according to Brooke and Kaiser (1970). IIc fibres were, however, so rare that they were not included in the final statistical analyses. Mean fiber areas were calculated from one selected portion of the biopsy sample with the average number of fibers (at pre- and post-training) of 85 and 62 recorded for the S group, and 63 and 52 for the SE group, respectively. A loaded image of stained cross-sections was analysed by the Tema Image-Analysis System (Scan Beam, Denmark). A videoscope consisting of a microscope (Olympus BX 50) and colour video camera (Sanyo High Resolution CCD) was used to calculate the mean fibre areas of each fibre type (Häkkinen et al. 2001a).

Aerobic performance

Maximal oxygen uptake ($\dot{V}O_{2\ max}$) test was carried out using the Ergoline Ergometrics 800S bicycle ergometer only for the SE group. The intensity was 75 W at the beginning of the test and was increased by 25 W every second minute until exhaustion. Heart rate was monitored continuously, and blood pressure before the test. The oxygen uptake ($\dot{V}O_2$) was measured continuously using the SensorMedics Vmax229. Blood samples were taken from fingertip every second minute to measure blood lactate concentrations and determine aerobic and anaerobic thresholds as described in detailed previously (Aunola and Rusko 1984). Blood lactate was determined using a Eppendorf Ebio 6666 lactate analyser.

Anthropometry

The fat percentage was estimated by measuring skin-fold thickness at four different sites according to Durnin and Womersley (1967).

Strength training and combined strength and endurance training

Strength training

The supervised 21-week strength training was carried out twice per week. Each training session included two exercises for the leg extensor muscles: the bilateral leg press exercise and the bilateral and/or unilateral knee extension exercise on the David 200 machine. In addition, each training session included four to five exercises for the other main muscle groups of the body (the bench press and/or the triceps pushdown and/or lateral pull down exercise for the upper body; the sit-up exercise for the trunk flexors and/or another exercise for the trunk extensors; and the bilateral/unilateral elbow and/or knee flexion exercise and/or leg adduction/abduction exercise). The exercises were so-called free motion machine exercises (David Fitness and Medical). The resistance was determined by the loads (kg) chosen on the weight stack, and the subject actively produced the motion and determined the action velocity by himself, and always performed a full range of motion in each exercise.

During the first 7 weeks of the training the subjects trained with loads of 50% to 70% of the 1RM. The subjects performed 10–15 repetitions per set and performed 3–4 sets of each exercise. The loads were 50% to 60% and 60% to 80% of the maximum during the second 7-week period. In the two exercises for the leg extensor muscles the subjects then performed either 8–12 repetitions per set (at lower loads) or 5–6 repetitions per set (higher loads) and performed 3–5 sets. In the other four exercises the subjects performed 10–12 repetitions per set and performed 3–5 sets. During the last 7 weeks of the training (weeks 15–21) two different load ranges were used in the two exercises for the leg extensors so that the subjects completed 3–6 repetitions per set with the loads of 70% to 80% of the maximum and 8–12 repetitions per set with the loads of 50% to 60%. The total number of sets varied between 4 and 6. In the other four exercises the subjects performed 8–12 repetitions per set and performed 3 to 5 sets altogether.

A major part of the knee extension exercises was performed using the basic principles of heavy resistance training but some (20%) of these exercises were performed with light loads (50% to 60% of the maximum) to meet the requirements of a typical explosive strength training protocol. Each repetition of each set with these light loads was executed as "explosively" as possible (rapid muscle actions) (Häkkinen et al. 1998b).

The loads were individually determined during the training sessions throughout the 21-week training period according to the maximum-repetition method. The overall amount of training was progressively increased until the 18th week at which point it was slightly reduced for the final 3 weeks of the 21-week training period.

Endurance training

Endurance training was also carried out twice per week. Thus, the SE group trained two times a week for strength (using the same program as the S group) and two more times a week for endurance. During the first 7 weeks the subjects trained twice a week for 30 min by bicycle ergometer or by walking to train basic endurance (under the aerobic threshold level), which was determined during the aerobic performance test before the intervention. All subjects applied pulse meters during training in order to maintain the intensity of exercise at the required level. On weeks 8–14 the duration of the first training session of 45 min was divided four loading levels: 15 min below the aerobic threshold level, 10 min between the aerobic-anaerobic thresholds, 5 min above the anaerobic threshold and 15 min again under the aerobic threshold. The second training session took 60 min and the training intensity was under the aerobic threshold level. The focus of the last 7 weeks of training was to improve cycling speed and maximal endurance carried out in a 60-min session as follows: 15 min under the aerobic threshold, 2×10 min between the aerobic–anaerobic thresholds, 2×5 min above the anaerobic threshold and the final 15 min under the aerobic threshold. The other training session of the week was basic endurance training (under the aerobic threshold) and it took 60–90 min.

Statistical methods

Standard statistical methods were used for the calculation of means, standard deviations (SD), standard errors (SE), and Pearson product moment correlation coefficients. The data were then analysed utilizing multivariate analysis of variance (MANOVA) with repeated measures. Probability adjusted t-tests were used for pairwise comparisons when appropriate. The $p < 0.05$ criterion was used for establishing statistical significance.

Results

Physical characteristics

No significant changes took place in the body mass or body fat percentage in the S group during the 21-week training period (Table 1). However, the SE group showed significant ($p < 0.05$ and 0.001) decreases in the body fat percentage throughout the experimental training period but no significant between-group differences occurred.

Bilateral 1RM leg extension values

No significant changes took place in the bilateral concentric 1RM leg extension action during the 1-week control period, while during the 21-week training period significant increases of 21% [from 184 (29) and 228 (29) kg] ($p < 0.001$) and 22% [171 (17) and 209 (24) kg] ($p < 0.001$) took place in the 1RM load in the S and SE groups, respectively (Fig. 1). The mean relative increases recorded for S and SE did not differ significantly from each other.

Maximal bilateral isometric leg extension force, RFD and iEMGs

No significant changes took place in the maximal bilateral isometric leg extension force during the 1-week control period, while during the 21-week training period significant increases of 22% ($p < 0.001$) and 21% ($p < 0.001$) were recorded in the S and SE groups, respectively (Fig. 2). The mean relative increases recorded for S and SE did not differ significantly from each other. No significant changes took place in the maximum iEMGs of the VL muscles of the right and left leg of the bilateral isometric leg extension action during the 1-week control period (Fig. 3a, b). During the 21-week training period significant increases of 26% ($p < 0.05$) and 29% ($p < 0.001$) took place in the maximum iEMG of the right VL in the S and SE groups, respectively (Fig. 3a). The corresponding iEMG increases for the left VL were 19% ($p < 0.05$) and 22% (ns) for the S and SE groups (Fig. 3b).

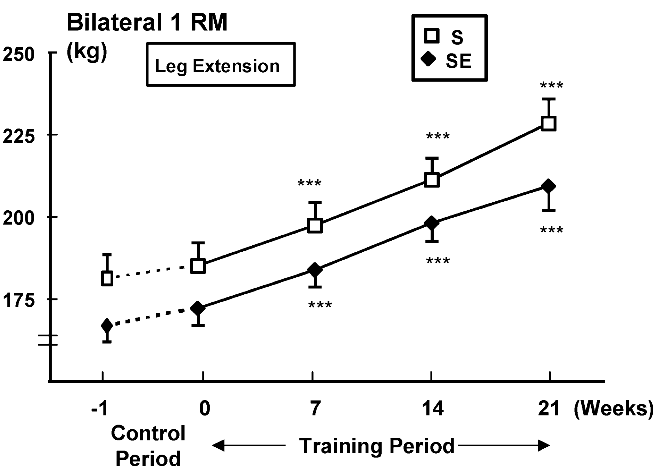

Fig. 1 Mean (with standard error) maximal voluntary leg extension one repetition maximum (*1RM*) strength in the strength training group (*S*) and combined strength and endurance training group (*SE*) during the 1-week control and 21-week training periods (***$p < 0001$)

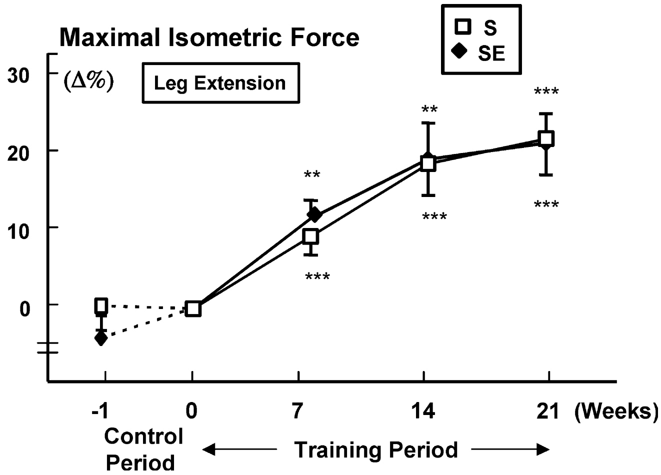

Fig. 2 Mean (with standard error) changes in maximal voluntary bilateral isometric leg extension force in the strength training group (*S*) and combined strength and endurance training group (*SE*) during the 1-week control and 21-week training periods (**$p < 001$; ***$p < 0001$)

The maximal RFD (Fig. 4) and average force produced during the first 500 ms remained unaltered during the control period in both groups. Throughout the 21-week training period the S group showed significant increases in RFD ($p < 0.01$) as well as in average force during the first 500 ms ($p < 0.01$) while no changes occurred in the SE group. The changes between the two groups differed significantly ($p < 0.001$). The average iEMG of the right VL muscle during the first 500-ms portion of the isometric action increased significantly ($p < 0.05$–0.001) during the training period in the S group, while no significant changes occurred in the SE group (Fig. 5). The corresponding iEMG increase for the left VL during the first 500-ms portion of the action was significant ($p < 0.05$ for weeks 7 and 14) only in the S group.

Maximal unilateral knee flexion force, RFD and iEMG

No significant changes took place in the maximal unilateral isometric knee flexion force of the right leg during the 1-week control period, while during the 21-week training period significant increases of 18% ($p < 0.05$ for week 7) and 22% ($p < 0.01$) were recorded in the S and SE groups, respectively. The two groups showed no significant changes in the maximum iEMG of the BF of the right knee flexion during the 1-week control period. During the 21-week training period insignificant increases of 20% and 13% were recorded in the maximum iEMG of the BF in the S and SE groups, respectively.

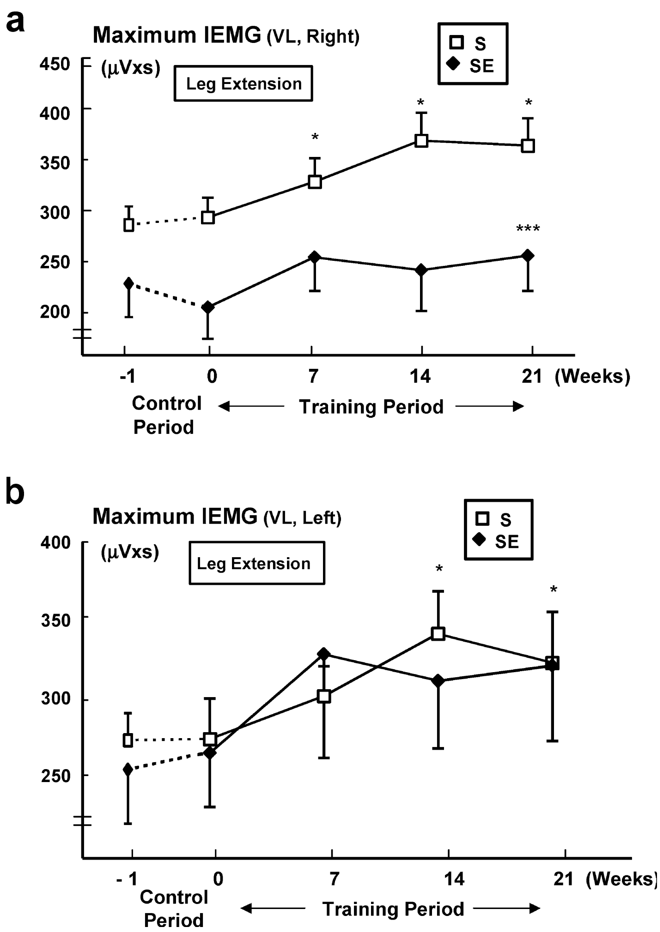

Fig. 3a, b Mean (with standard error) maximum integrated electromyographic activity (*iEMG*) of the vastus lateralis (*VL*) of the right leg (**a**) and left leg (**b**) in the voluntary maximal bilateral isometric leg extension action in the strength training group (**S**) and combined strength and endurance training group (**SE**) during the 1-week control and 21-week training periods (*$p < 005$; ***$p < 0001$)

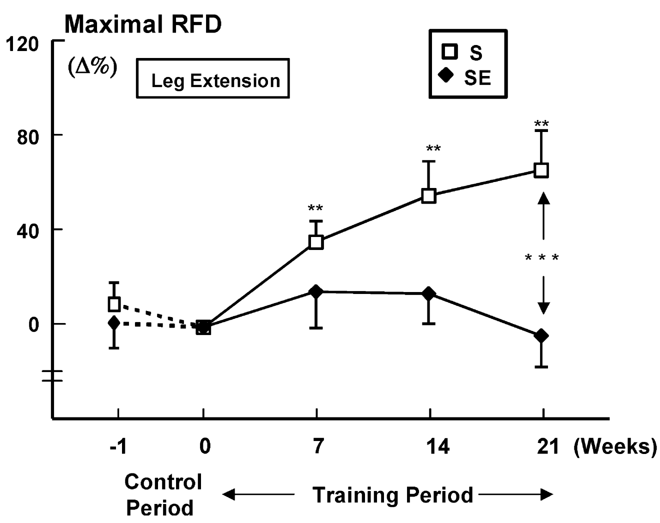

Fig. 4 Mean (with standard error) changes in maximal rate of force development (*RFD*) in the rapidly produced voluntary bilateral isometric leg extension action in the strength training group (*S*) and combined strength and endurance training group (*SE*) during the 1-week control and 21-week training periods (**$p < 001$; ***$p < 0001$)

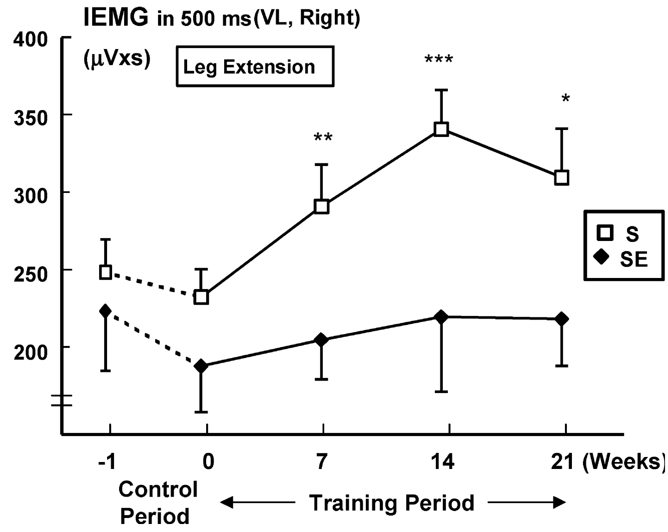

Fig. 5 Mean (with standard error) averaged integrated electromyographic activity (*iEMG*) of the vastus lateralis (*VL*) of the right leg during the first 500 ms in the rapidly produced voluntary bilateral isometric leg extension action in the strength training group (*S*) and combined strength and endurance training group (*SE*) during the 1-week control and 21-week training periods (*$p < 005$; **$p < 001$; ***$p < 0001$)

The maximal RFD of the knee flexion remained unaltered during the control period in both groups. Throughout the 21-week training period the S group showed significant increases in RFD ($p < 0.01$), while no significant increases occurred in the SE group. The change between the two groups differed significantly ($p < 0.001$).

Antagonist IEMGs

The BF activities of the right leg (relative to maximum agonist values of the BF) during the bilateral isometric leg extension remained unaltered during the 1-week control period in both groups. During the 21-week training period it remained statistically unaltered in S [from 29 (21) to 31 (24)%] but decreased in SE [from 27 (10) to 21 (8)%; $p < 0.05$].

Muscle CSA

The CSA of the QF increased during the 21-week training period throughout the length of the muscle from 4/15 to 12/15 L_f in both S ($p < 0.05$–0.001) and SE ($p < 0.01$–0.001) (Fig. 6a, b). The mean relative increases (mean of 5/12 to12/15 L_f) of the QF of 6% and 9% recorded for the S and SE groups did not differ significantly from each other. Similarly, the significant increases of 7% ($p < 0.001$) and 9% ($p < 0.001$) of the QF at its largest portion (L_f 9/15) recorded for the S and SE groups during the 21-week training period did not differ from each other.

Muscle fibre characteristics

The percentage values for the muscle fibre distribution of the VL muscle did not differ significantly before or after the training period in the S or SE groups (Table 2). However, there were trends for the decreases in the percentage of type IIb fibres in both S ($p = 0.072$) and SE ($p = 0.089$). The mean fibre CSA of type I as well as those of type IIa and IIb increased after the 21-week training period in both S ($p < 0.05$ and 0.01) and SE ($p < 0.05$ and $p < 0.01$) (Table 3). The relative increases between the two groups did not differ significantly from each other.

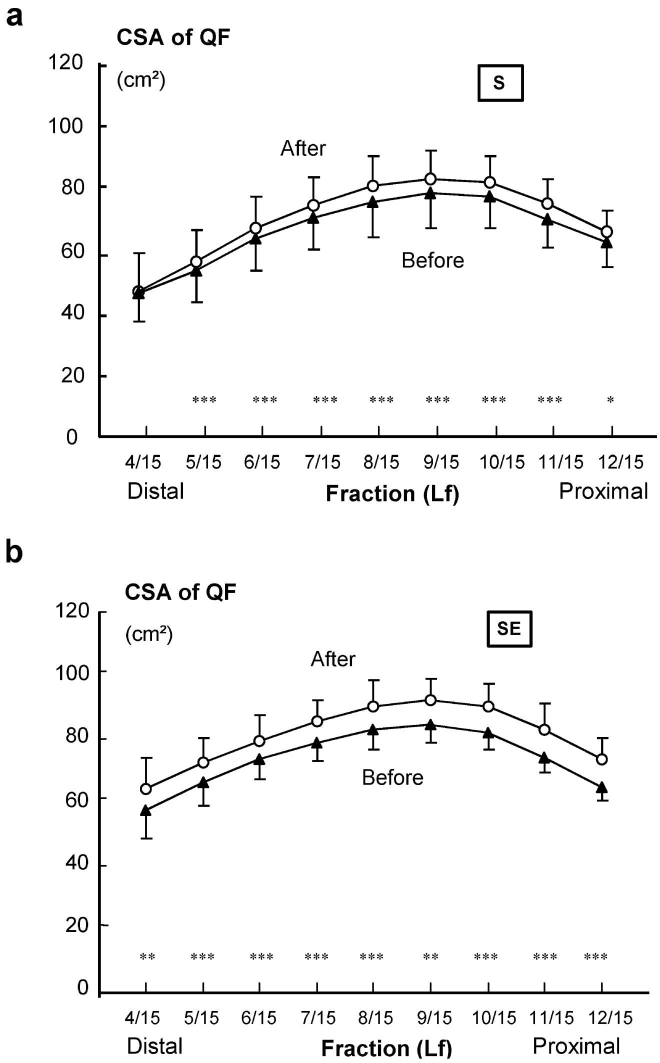

Fig. 6a, b Mean (with standard error) cross-sectional areas (*CSA*) of the total quadriceps femoris (*QF*) muscle group at the lengths of from 4/15 to 12/15 of the femur (L_f) in the strength training group (*S*) (**a**) and combined strength and endurance training group (*SE*) (**b**) before and after the 21-week training period (*$p < 005$, **$p < 001$; ***$p < 0001$)

Maximal oxygen uptake

$\dot{V}O_{2max}$ increased during the 21-week training period by 18.5% ($p < 0.001$) in the SE group (Fig. 7). Maximal power at the maximal performance increased by 17% ($p < 0.001$), and the intensity (expressed in watts) that elicited the aerobic and anaerobic thresholds increased by 16% ($p < 0.01$), and 14% ($p < 0.01$), respectively. No significant changes occurred in the maximal heart rate [191 (8) and 189 (12) beats/min], or in the heart rates at the anaerobic or aerobic thresholds during the 21-week training period.

Discussion

The primary purpose of this study was to investigate the effects of concurrent strength and endurance training in men over an extended training period of 21 weeks. The training volume was diluted by a longer period of time with a low frequency of training. The present subjects utilized a comprehensive resistance training program which addressed both strength and power components of fitness. We monitored the hypertrophy at both the cellular and whole-body levels and combined this with the evaluation of voluntary neural activation measures of the thigh musculature. The primary findings of this investigation were that concurrent strength and endurance training resulted in large gains in maximal strength accompanied with significant enlargements in the CSA of the QF and in the sizes of individual muscle fibres. In addition, increased maximal voluntary neural activation of the trained muscles was also observed. The magnitudes of these increases did not differ from the corresponding changes observed in the group that performed strength training alone. However, the present strength/power training program also resulted in significant increases in rapid force production of the trained leg extensors associated with significant increases in the rapid neural activation of these muscles. No changes took

Table 2 Mean (SD) fibre distribution of the vastus lateralis muscle before and after a 21-week strength training period in the strength (*S*) ($n = 10$) and strength and endurance(*SE*) ($n = 8$) groups

	S Group				SE Group			
	Pre		Post		Pre		Post	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Type I (%)	34	(12)	37	(13)	35	(12)	41	(14)
Type IIa (%)	16	(15)	26	(19)	26	(12)	30	(16)
Type IIb (%)	50	(16)	36	(13)	38	(15)	28	(17)

Table 3 Mean (SD) fibre areas of the vastus lateralis muscle before and after the 21-week training period in the strength (*S*) ($n = 10$) and strength and endurance (*SE*) ($n = 8$) groups

	S Group				SE Group			
	Pre		Post		Pre		Post	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Type I (μm^2)	5022	(1060)	7338*	(2471)	6149	(2069)	6974*	(2250)
Type IIa (μm^2)	5577	(1659)	7022**	(1544)	6816	(1524)	8378*	(2368)
Type IIb (μm^2)	4836	(1389)	6703**	(1677)	5660	(1909)	7439**	(2088)

Significant difference pre–post training (*$p < 0.05$; **$p < 0.01$)

place in these special neuromuscular characteristics when strength training was combined with endurance training.

The present 21-week training period, despite the fact that strength training was performed only twice per week, led to large increases of 21% and 22% in bilateral concentric 1RM strength of the leg extensors in groups S and SE, respectively. Thus, diluting the time given to resistance exercise stimuli did not affect the changes in physically active men. The increases in maximal isometric leg extension forces were also of the same magnitude, namely 22% and 21% in the S and SE groups, respectively. Thus, no significant differences existed in the strength development between the two groups. In general, the magnitudes of the present strength gains were well within the ranges reported to take place during pure strength training using the same volume of training in previously untrained subjects, independent of age and gender (Häkkinen et al. 1998b, 2001a, 2001b). An important conclusion from the practical point of view is that the frequency of strength training in previously untrained adults can be as low as twice a week when the loading intensity of training is sufficient and increased progressively (i.e. periodized) throughout the training period. The strength gains of the lower extremities took place gradually throughout the 21-week training period (Figs. 1 and 2) showing clearly that the strength development was not influenced adversely by the simultaneous endurance training, as some others have found (e.g. Kraemer et al. 1995; McCarthy et al. 1995, 2002). Therefore, the present data do not support the concept of the universal nature of the ‘‘interference effect’’that has been described by Hickson (1980) in strength development when strength training is performed concurrently with endurance training. However, it should be noted that, compared to the present study, Hickson (1980) used a condensed period of time with a higher frequency (and volume) of training. The interference effect may also hold true when the overall volume and/or frequency of training is higher over a longer period of time, so that simultaneous training for both strength and endurance may be associated with large strength gains during the initial weeks of training but with only limited strength development during the later months of training. As the training for physical fitness calls for the development of muscle strength and endurance, the present findings suggest that this type of systematic training for strength and endurance, even with only two sessions per week, can be beneficial when performed for a prolonged period and can be utilized for various practical applications.

It has been well documented that in previously untrained adults, middle aged and older subjects large increases in maximal strength observed during the initial weeks of strength training can be attributed largely to the increased motor unit activation of the trained agonist muscles (Moritani and DeVries 1979, 1980; Häkkinen and Komi 1983; Häkkinen et al. 1998b, 2001a, 2001b). This concept was well supported by the large increases observed in the maximum iEMGs of the leg extensors not only in the pure strength trained group but maximal strength development was mediated by the increased maximal voluntary activation of the trained muscles to about the same extent also in the concurrent strength and endurance training group. The findings indicate that the contributing role of the nervous system to maximal strength development during the present training period in both groups may have been greatly important. Strength-training-induced increases in the magnitude of the EMG could result from the increased number of active motor units and/or an increase in their firing frequency (Sale 1992; Häkkinen 1994). Thus, the present results do indicate a lack of interference for the SE group in the neural adaptations during the maximal

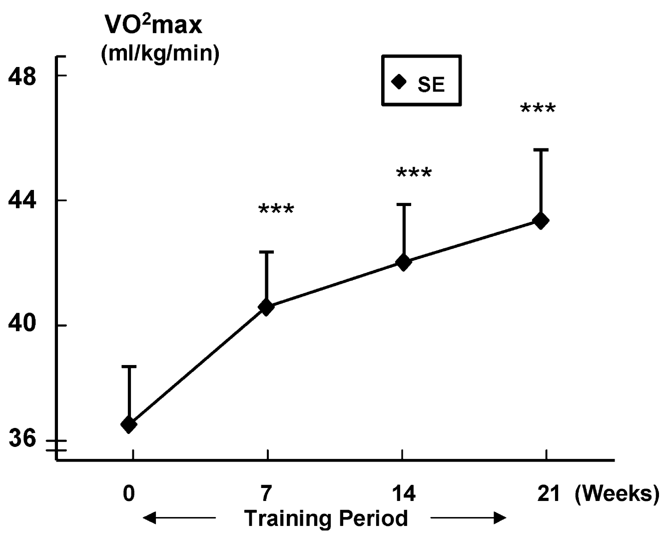

Fig. 7 Mean (with standard error) maximal oxygen uptake ($\dot{V}O_{2max}$) recorded in the bicycle ergometer test in the combined strength and endurance training group (*SE*) during 21-week training period ($^{***}p < 0001$)

force phase of the contraction when there is enough time, such as 1–2 s, to activate the muscles maximally to produce the maximal peak force. The coactivation of the BF muscle recorded during the leg extension action was within the normal levels in both groups (Häkkinen et al. 1998a, 1998b), and no drastic changes were observed during the training period. However, the present data did indicate that there was some reduction in the coactivation of the antagonist muscles in the SE group, which may have also contributed to enhance the net strength development of the agonists (Häkkinen et al. 1998b). A plausible explanation of the concurrent training-induced decreases in the antagonist coactivation of the BF muscle group could be related to the important role that the BF (together with the gluteus maximus) has in hip/knee extension and/or flexion during the propulsion and recovery phases of the pedal stroke (Gregor and Rugg 1986).

Measures of fibre area by muscle biopsy and of muscle CSA by MRI were used to examine how much muscle hypertrophy may have contributed to the strength gains observed in the present study. The present progressive strength training program, although performed only twice a week, did lead to significant increases during the 21-week period in the mean fibre areas of type I and of types IIa and IIb in both S and SE groups. The relative magnitude of muscle fibre hypertrophy was similar between the two groups, and well within the enlargements reported previously during pure strength training with two sessions per week in middle-aged men and women (Häkkinen et al. 2001a). However, it is likely that if the training frequency had been higher, greater gains in the fibre size would have taken place, at least in the pure strength training group (Kraemer et al. 1995). It has been suggested that a lack of change in the size of skeletal muscles may be an underlying reason for the depressed gains in maximal strength observed after concurrent strength and endurance training (Bell et al. 1991; Kraemer et al 1995). This may be partly due to the oxidative stress imposed on the muscle and the need to optimize the kinetics of oxygen transfer because of the addition of endurance training to strength training. However, our findings in adult men suggest that hypertrophy of individual muscle fibres of types I and II is similar between strength training and concurrent strength and endurance training when the frequency of training is low. Therefore, the present strength training stimuli, although performed only twice a week but for a long period of 21 weeks, may allow adaptations due to the extended presentation of the exercise stimuli. However, some caution must be exercised when interpreting the present muscle fibre data, as a relatively low number of fibres were analysed and the biopsy samples were obtained only at one particular position in the thigh (Narici et al. 1996; Häkkinen et al. 2001b). Therefore, we also used the multiple-slice method in the MRI scanning to estimate the accurate muscle CSA changes in all regions of the QF. The present MRI data did show that the increases in the CSA of the total QF took place throughout the length of the femur (from 4/15 to 12/15 L_f) suggesting strongly that the degree of overall muscle hypertrophy was very similar between the S and SE groups. It is also possible that architectural changes, e.g. changes in pennation angle of the muscle fibres, may have taken place during the present strength training period (e.g. Kawakami et al. 1993).

The present strength training program was composed not only of heavy resistance but also, to some extent, of explosive types of exercises for the leg extensor muscles. The exercises were machine exercises but the resistance was determined by the load chosen on the weight stack, and the subject actively produced the motion himself, trying to obtain in explosive exercises as high an action velocity as possible throughout the full range of motion. This type of training regimen has previously been shown to lead to increased explosive force production recorded in both isometric and dynamic actions (Häkkinen et al. 1998b). In addition to the gains in maximal force, the present training also led to considerable increases in the RFD and in the average force during the first 500 ms indicating improved explosive strength of the trained muscles in group S. The increases observed in explosive strength during the present strength training indicate that considerable training-induced changes may have taken place in the voluntary and/or reflexly induced rapid neural activation of the motor units of the trained muscles as shown previously in both middle-aged and elderly men and women (Häkkinen et al. 1998b). Actually, this was supported by the observation that the average iEMG of the VL muscles during the first 500 ms of the isometric action increased significantly during the training period in group S. However, the present study showed that although the pure strength training resulted in significant increases in rapid force production of the trained leg extensors associated with the significant increases in rapid neural activation of these muscles, no changes took place in these special neuromuscular characteristics when strength training was combined with endurance training. This agrees with studies finding that concurrent strength and endurance training performed with a high frequency of training (six to ten training sessions per week) interferes with some indicators of explosive strength development, such as vertical jump (Hunter et al. 1987) and angle-specific maximal torque at fast velocities of contraction (Dudley and Djamil 1985). The present results suggest that the low frequency of concurrent strength and endurance training (four training sessions per week) also leads to interference in explosive strength development, probably mediated by a reduced improvement in rapid voluntary neural activation. Training-induced adaptations in the neuromuscular system are known to differ according to the specific mode of exercise used for strength training; for example, between typical maximal strength training regimens and explosive strength training protocols (Häkkinen et al 1985a, 1985b). Therefore, this specificity, in terms of functional adaptations caused by an explosive type of strength training, seems to play some role in the degree of the antagonism caused by the present type of combined strength and endurance training. In general terms, the present findings also support well the suggested explanations given by Bell et al. (2000) for the discrepancies between many research results; namely, differences in the type of strength training and endurance training, experimental design, subject sample, design of the training program and the sensitivity of the dependent variable (see Leveritt et al. 1999). Nevertheless, since both maximal muscle strength and RFD, which reflects the ability of the leg extensor muscles to develop force rapidly, are important performance characteristics contributing to several tasks of daily life such as climbing stairs, walking, or even the prevention of falls and/or trips (Bassey et al. 1992; Izquierdo et al. 1999), the optimal construction and/or periodical prioritization of maximal strength and/or explosive strength and/or endurance exercises is important for overall fitness training among adults and especially older people. The role of RFD becomes naturally increasingly important for various athletic purposes.

The present 21-week combined strength and endurance training program did significantly improve aerobic performance capacity, since $\dot{V}O_{2max}$ increased by as much as 18.5%. The increase was slightly less than that recorded for maximal strength of the lower extremities but rather similar in magnitude to those increases in aerobic performance reported to take place during combined strength and endurance training in previously untrained men (Hickson 1980; Dudley and Djamil 1985; McCarthy et al. 1995; Bell et al. 1997, 2000). Thus, it seems that the addition of endurance training does not impair the magnitude of increase in aerobic power induced by endurance training alone (e.g. McCarthy et al. 1995; Bell et al. 1997, 2000). This is well in line with the concept that central circulation is the predominant factor that limits maximal aerobic power during exercise with large muscle group involvements. Although strength training may lead to peripheral changes that could be considered antagonistic to aerobic power development, e.g. reductions in muscle mitochondria, capillary, and aerobic enzymes, central circulatory adaptations related to enhancement of aerobic power seem only slightly affected by strength training (Hurley et al. 1984; McCarthy et al. 1995). The present findings also have some practical relevance, as maximal aerobic performance in adult men can be increased by using a frequency of as low as twice per week for endurance, when the training program meets the requirements of progressiveness and individualization, and is based on the true monitoring of each training session. Whether the increases were compromised or facilitated by the simultaneous strength training cannot be determined, because no aerobic measures were taken from the present strength training group, and no separate group training for endurance only was included in the present experimental design.

In conclusion, the present data do not support the concept of the universal nature of the "interference effect" in strength development and muscle hypertrophy when strength training is performed concurrently with endurance training. However, this interference effect may hold true with regard to explosive strength development associated with limited changes in rapid neural activation of the trained muscles. Second, the interference effect may also be true when the overall frequency and/or volume of training is higher than in the present study so that simultaneous training for both strength and endurance may be associated with large strength gains during the initial weeks of training but with only limited strength development during later months of training. As the training for physical fitness calls for the development of muscle strength, power and endurance, the present findings indicate that construction and/or periodical prioritization of maximal strength and/or explosive strength and/or endurance exercises is important for overall fitness training.

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References

Åstrand P-O, Rodahl K (1986) Textbook of work physiology. Physiological bases of exercise, 3rd edn. McGraw-Hill, New York
Aunola S, Rusko H (1984) Reproducibility of aerobic and anaerobic thresholds in 20–50 year old men. Eur J Appl Physiol 53:260–266
Bassey EJ, Fiatarone MA, O'Neill EF, Kelly M, Evans WJ, Lipsitz LA (1992) Leg extensor power and functional performance in very old men and women. Clin Sci 82:321–327
Bell GJ, Petersen SR, Wessel J, Bagnall K, Quinney HA (1991) Physiological adaptations to concurrent endurance training and low velocity resistance training. Int J Sports Med 12:384–390
Bell GJ, Syrotuik D, Socha T, MacLean I, Quinney HA (1997) Effect of strength training and concurrent strength and endurance training on strength, testosterone and cortisol. J Strength Condit Res 11:57–64
Bell GJ, Syrotuik D, Martin TP, Burnham R, Quinney HA (2000) Effect of concurrent strength and endurance training on skeletal muscle properties and hormone concentrations in humans. Eur J Appl Physiol 81:418–427
Bergström J (1962) Muscle electrolytes in man. Scand J Clin Lab Invest Suppl 68
Brooke MH, Kaiser KK (1970) Three "myosin ATPase" systems: the nature of their pH lability and sulfhydryl dependence. J Histochem Cytochem 18:670–672
Dudley GA, Djamilj R (1985) Incompatibility of endurance- and strength-training modes of exercise. J Appl Physiol 59:1446–1451
Durnin J, Womersley Y (1967) Body fat assessed from total body density and its estimation from skinfold thickness: measurement on 481 men and women aged from 16 to 72 ages. Br J Nutr 32:77–97
Gregor RJ, Rugg SG (1986) Effects of saddle height and pedaling cadence on power output and efficiency. In: Burke ER (ed) Science of cycling. Human Kinetics, Champaign, Ill.
Häkkinen K (1994) Neuromuscular adaptation during strength training, aging, detraining, and immobilization. Crit Rev Physiol Rehab Med 6:161–198
Häkkinen K, Komi PV (1983) Electromyographic changes during strength training and detraining. Med Sci Sports Exerc 15:455–460

Häkkinen K, Alen M, Komi PV (1985a) Changes in isometric force and relaxation-time, electromyographic and muscle fibre characteristics of human skeletal muscle during strength training and detraining. Acta Physiol Scand 125:573–585
Häkkinen K, Komi PV, Alen M (1985b) Effects of explosive type strength training on isometric force- and relaxation time, electromyographic and muscle fibre characteristics of leg extensor muscles. Acta Physiol Scand 125:587–600
Häkkinen K, Alen M, Kallinen M, Izquierdo M, Jokelainen K, Lassila H, Mälkiä E, Kraemer WJ, Newton RU (1998a) Muscle CSA, force production, and activation of leg extensors during isometric and dynamic actions in middle-aged and elderly men and women. J Aging Phys Act 6:232–247
Häkkinen K, Kallinen M, Izquierdo M, Jokelainen K, Lassila H, Mälkiä E, Kraemer WJ, Newton RU, Alen M (1998b) Changes in agonist-antagonist EMG, muscle CSA and force during strength training in middle-aged and older people. J Appl Physiol 84:1341–1349
Häkkinen K, Kraemer WJ, Newton RU, Alen M (2001a) Changes in electromyographic activity, muscle fibre and force production characteristics during heavy resistance/power strength training in middle-aged and older men and women. Acta Physiol Scand 171:51–62
Häkkinen K, Pakarinen A, Kraemer WJ, Häkkinen A, Valkeinen H, Alen M (2001b) Selective muscle hypertrophy, changes in EMG and force, and serum hormones during strength training in older women. J Appl Physiol 91:569–580
Hickson RC (1980) Interference of strength development by simultaneously training for strength and endurance. Eur J Appl Physiol 215:255–263
Holloszy J, Coyle E (1984) Adaptations of skeletal muscle to endurance exercise and their metabolic consequences. J Appl Physiol 56:831–838
Hortobagyi T, Katch F, Lachance P (1991) Effects of simultaneous training for strength and endurance. J Sports Med Phys Fitness 31:20–20
Hunter G, Demment R, Miller D (1987) Development of strength and maximum oxygen uptake during simultaneous training for strength and endurance. J Sports Med Phys Fitness 27:269–275
Hurley B, Seals D, Eshani A, Cartier L, Dalsky G, Hagberg J, Holloszy J (1984) Effects of high intensity strength training on cardiovascular functions. Med Sci Sports Exerc 16:483–488
Izquierdo M, Aguado X, Gonzalez R, López JL, Häkkinen K (1999) Maximal and explosive force production capacity and balance performance in men of different ages. Eur J Appl Physiol 79:260–267
Kawakami Y, Abe T, Fukunaga T (1993) Muscle-fibre pennation angles are greater in hypertrophied than in normal muscles. J Appl Physiol 74:2470–2744
Komi PV (1986) Training of muscle strength and power: interaction of neuromotoric, hypertrophic and mechanical factors. Int J Sports Med (Suppl) 7:10–15
Kraemer WJ, Patton JF, Gordon SE, Harman EA, Deschenes MR, Reynolds K, Newton RU, Triplett NT, Dziados JE (1995) Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. J Appl Physiol 78:976–989
Leveritt M, Abernethy PJ, Barry BK, Logan PA (1999) Concurrent strength and endurance training. A review. Sports Med 28:413–427
MacDougall J (1992) Hypertrophy or hyperplasia. In: Komi PV (ed) Strength and power in sports. The encyclopedia of sports medicine. Blackwell, Oxford, Chapter 8B
McCarthy JP, Agre JC, Graf BK, Pozniak MA, Vailas AC (1995) Compatibility of adaptive responses with combining strength and endurance training. Med Sci Sports Exerc 27:429–36
McCarthy JP, Pozniak MA, Agre JC (2002) Neuromuscular adaptations to concurrent strength and endurance training. Med Sci Sports Exerc 34:511–519
Moritani T, DeVries HA (1979) Neural factors versus hypertrophy in the time course of muscle strength gain. Am J Phys Med 58:115–130
Moritani T, DeVries HA (1980) Potential for gross muscle hypertrophy in older men. J Geriatr 35:672–682
Narici M, Hoppeler H, Kayser B, Landoni L, Claasen H, Gavardi C, Conti M, Cerretelli P (1996) Human quadriceps cross-sectional area, torque, and neural activation during 6 months strength training. Acta Physiol Scand 157:175–186
Sale DG (1992) Neural adaptation to strength training. In: Komi PV (ed) Strength and power in sports. The encyclopedia of sports medicine. Blackwell, Oxford, Chapter 9A
Sale D, MacDougall J, Jacobs I, Garner S (1990) Interaction between concurrent strength and endurance training. J Appl Physiol 68:260–356