

Neuromuscular and Cardiovascular Adaptations During Concurrent Strength and Endurance Training in Untrained Men

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Key words

- maximal strength
- resistance training
- endurance performance
- rate of force development
- muscle hypertrophy

Abstract

▼ This study examined the effects of concurrent strength and endurance training on neuromuscular and endurance characteristics compared to strength or endurance training alone. Previously untrained men were divided into strength (S: n=16), endurance (E: n=11) or concurrent strength and endurance (SE: n=11) training groups. S and E trained 2 times and SE 2+2 times a week for strength and endurance during the 21-week period. Maximal unilateral isometric and bilateral concentric forces of leg muscles increased similarly in S and SE by 20–28% ($p<0.01$) and improvements in isometric forces were accompanied by increases ($p<0.05$) of

maximal muscle activation. Rate of force development of isometric action ($p<0.05$) improved only in S. The increase in muscle cross-sectional area of the quadriceps femoris in SE (11%, $p<0.001$) were greater than in S (6%, $p<0.001$) or in E (2%, $p<0.05$). SE and E increased maximal cycling power (SE: 17% and E: 11%, $p<0.001$) and VO_{2MAX} (SE: 17%, $p<0.001$ and E: 5%, ns.). These results suggest that the present moderate volume 21-week concurrent SE training in previously untrained men optimizes the magnitude of muscle hypertrophy, maximal strength and endurance development, but interferes explosive strength development, compared with strength or endurance training alone.

Introduction

▼ Typical strength training leads to neural and hypertrophic adaptations responsible for improved strength performance of the trained muscles. Neural adaptations (e.g. increased motor unit recruitment and/or increase in their firing frequency) take place primarily during the first weeks of training and when strength training is continued for several weeks, the role of hypertrophic adaptations becomes increasingly important [14,37]. On the other hand, endurance training improves aerobic performance by increasing maximal oxygen uptake and its cardiovascular determinants [13,41].

In many sports athletes have to train both endurance and strength training concurrently. In addition, to promote and maintain good health and physical independence it is important to enhance both cardiovascular and neuromuscular fitness [e.g. 9]. It has been suggested that concurrent endurance and strength training can lead to conflicting neuromuscular adaptations and might interfere or inhibit strength development, if the

concurrent training period is too long and/or the training volume, intensity or frequency ($4-6 d \times wk^{-1}$) is too high, since strength and endurance training induce distinct and often divergent adaptive physiological adaptations [e.g. 3,11,26,33,37]. This possible interference has been attributed to the development of residual fatigue in the neuromuscular system as a consequence of the high volume and training frequency. The chronic interference hypothesis suggests that trained muscles are unable to adapt optimally at the same time morphologically or metabolically to both strength and endurance training stimulus [26,33]. Interference in strength development may also relate to overtraining symptoms induced by a catabolic hormonal environment and chronic muscle glycogen depletion because of too high training frequency or volume [25,33].

However, several studies in previously untrained subjects have shown that concurrent training may not have an inhibitory effect on the development of strength or endurance variables especially when the training frequency varies

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between 1–2 times per week for both strength and endurance [e.g. 22, 30, 38]. In addition, it seems that in endurance athletes concurrent training does not alter the ability to adapt to endurance training [6, 12, 23, 32] and athletes may even improve endurance performance and performance affecting factors (e.g. performance economy, neuromuscular characteristics) during a strength emphasized training period, although high volume of endurance training is performed concomitantly [e.g. 6, 35, 40]. Many of the previous concurrent training studies in previously untrained men have investigated the effects of relatively short term (from 7 to 16 weeks) periods [3, 7, 20, 22, 30, 31]. However, there are a few studies [34, 38, 39] that have utilized a prolonged (20–22 weeks) concurrent strength and endurance training program. Sillanpää et al. [39] showed that combined strength and endurance training is effective to improve both muscle force and VO_{2MAX} in middle-aged and older men (40–65 years). However, because older people have lower initial force levels, already the endurance training by bicycle may give more training stimulus in strength development in older people than in adults aged 20–40 years. In addition, in older people muscles have changed into “more slow” [27]. These differences may lead to somewhat different training adaptations to concurrent strength and endurance training in adults and older men. Thus, there is a lack of data of the concurrent strength (heavy and explosive) and endurance training adaptations over a prolonged time in previously untrained adult men. Therefore, the purpose of this study was to investigate the role of neural and hypertrophic adaptations in strength development as well as the degree of aerobic performance improvement during prolonged concurrent strength and endurance training compared to strength or endurance training alone in adult men. Especially we wanted to investigate the effects of moderate total volume (frequency) training to avoid possible overtraining effects. Moreover, the strength training utilized in the present study was programmed to enhance both maximal and explosive strength.

Methods



Subjects

44 healthy adult men were recruited for the study. 6 subjects dropped out during the study period (for various personal reasons) so that 16 subjects were left in the strength training (S) group, 11 in the concurrent strength and endurance training (SE) group and 11 in the endurance training (E) group. Physical characteristics of the subject groups are presented in **Table 1**. None of the subjects had any background in regular strength and endurance training or competitive sports of any kind. Subjects were not on any medications that would affect physical per-

formance. 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 ethical standards of the International Journal of Sports Medicine [8] and to the declaration of Helsinki and was approved by the Ethics Committee of the University of Jyväskylä, Finland.

Experimental design

The total duration of the present study was 22 weeks. The subjects were tested on 5 different occasions using identical strength testing 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. The subjects were tested before and after this control period. Thereafter, the subjects started a supervised experimental training period for 21 weeks either in the S, SE or E group. The measurements were repeated during the actual experimental training period at 7-week intervals (i.e. weeks 0, 7, 14 and 21). Aerobic performance test and hormonal measurements were not done before the control period (-1) and the hypertrophic measurements (MRI) were carried out only at weeks 0 and 21. The present paper contains the overall results of the large study design and a selected part of the data has been reported previously [16].

Strength training

Progressive and supervised strength training of totally 21 weeks was carried out 2 times per week (**Table 2**). Each training session included 2 exercises for the leg extensor muscles: the bilateral leg press and the knee extension exercise. In addition, each training session included 5 exercises for the other main muscle groups of the body according to the given session program (upper body: the bench press or lateral pull down exercise, arms: the triceps pushdown or biceps curl, trunk: the sit-up exercise or trunk extensors exercise, lower body: knee flexion exercise or calf raises, and leg adduction or abduction exercise). A major part of the leg press and knee extension exercises were performed using the basic principles of heavy resistance training. A part (20%) of these exercises were performed with light loads (50–60% of the maximum) as explosively as possible to meet the requirements of a typical explosive strength training protocol [17]. 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 strength 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.

Table 1 Basic characteristics of the subjects during the training period.

	Group E		Group SE		Group S	
	Height (cm)	Age (yrs)	Height (cm)	Age (yrs)	Height (cm)	Age (yrs)
Week 0	181 ± 8	37 ± 7	181 ± 8	37 ± 5	178 ± 5	38 ± 6
Week	Body mass kg	Fat %	Body mass kg	Fat %	Body mass kg	Fat %
0	79.8 ± 13.0	17.6 ± 3.6	88.6 ± 12.9	22.5 ± 4.5	84.7 ± 15.6	20.3 ± 5.2
7	79.8 ± 13.2	17.4 ± 3.8	88.2 ± 11.9	21.6 ± 4.5	85.4 ± 16.4	20.7 ± 5.1
14	80.1 ± 13.3	17.3 ± 3.9	88.1 ± 11.9	21.3 ± 4.5**	85.1 ± 16.3	20.6 ± 5.2
21	80.3 ± 13.3	17.3 ± 3.9	87.3 ± 11.5	20.2 ± 4.4**, †	85.9 ± 18.1	20.4 ± 5.3

Note: Values are means ± sd. **p < 0.01; compared to week 0, †p < 0.01; compared to week 7

Table 2 Training programme during the 21-week period.

Training weeks	1–7	8–14	15–21
strength training sessions 2 times a week			
leg press and knee extension	3–4 × 10–15 RM (50–70% of 1RM)	2–3 × 8–12 (50–60% of 1RM) 2–3 × 5–6 (60–80% of 1RM)	2–3 × 8–12 (50–60% of 1RM) 2–3 × 3–6 (70–80% of 1RM)
other exercises	3–4 × 10–15 RM	3–5 × 10–12 RM	3–5 × 8–12 RM
endurance training sessions 2 times a week			
session 1	cycling ergometer 30 min under AerT intensity	cycling ergometer 45 min including 10 min at intensity AerT – AnT+5 min >AnT	cycling ergometer 60 min including 2 × 10 min at intensity AerT – AnT+2 × 5 min >AnT
session 2	cycling or Nordic walking 30 min under AerT intensity	cycling or Nordic walking 60 min under AerT intensity	cycling or Nordic walking 60–90 min under AerT intensity

Note: All strength training sessions and endurance session 1 were supervised. AerT = aerobic threshold, AnT = anaerobic threshold [1]. About 20% of leg exercises were performed as explosively as possible (with light loads of 50–60% of 1RM) [15]. All subjects included in the final analyses carried out at least 90% of the planned strength and endurance training sessions

Endurance and concurrent training

Endurance training was also carried out 2 times per week for 21 weeks (• **Table 2**). Thus, the SE group trained 2 times a week for strength (using the same program as the S group) and 2 more times a week for endurance (using the same program as the E group). The strength and endurance training sessions were executed on separate days. The training intensities were determined from an incremental bicycle ergometer test before the intervention and they were updated in weeks 7 and 14. All subjects applied heart rate monitors during training in order to maintain the intensity of exercise at the required level. The focus of the first 7-week training was to accustom oneself to endurance training and improve basic endurance. The endurance training intensity and volume increased progressively (• **Table 2**) during the 21-week period so that the focus of the last 7 weeks of training was to improve maximal cycling capacity.

Muscle strength measurements

The subjects were carefully familiarized with the testing procedures of voluntary force production of the muscle groups tested. During the actual testing occasion 2–3 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.

Maximal rate of isometric force development (RFD) and maximal isometric force of the unilateral knee extensor muscles of the right leg were measured using the modified David 200 dynamometer (David Fitness and Medical Ltd) [17]. The subject performed on verbal command a maximum isometric action in order to produce force as fast as possible during a period of 2–3 s. A minimum of 3 trials was completed for each subject and the best performance trial with regard to maximal peak force was used for the subsequent statistical analysis. Unfortunately, in the SE group the data recorded for the knee extension measurements at 0 week had to be rejected due to unresolved technical problems of the data recording. Because of that, the whole data set in all groups were replaced by the data recorded at week-1.

A David 210 dynamometer (a seated leg press) was used to measure maximal bilateral concentric force production of the leg extensors (hip, knee and ankle extensors) [15]. On verbal command the subject performed a concentric leg extension starting from a flexed position of knee angle at 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 1 RM contractions were performed with

1 min rest between contractions. The last acceptable extension with the highest possible load was determined as 1 RM.

The force signal was recorded on a computer and thereafter digitized and analyzed with a Cudas TM computer system (Data Instruments, Inc.). Maximal peak force was defined as the highest value of the force (N) recorded during the isometric actions. The maximal rate of force development (RFD; $N \times s^{-1}$) was analyzed and defined as the greatest increase in force in a given 50 ms time period [15].

EMG measurements

Electromyographic (EMG) activity during the unilateral knee extension action was recorded from the agonist vastus medialis (VM) of the right leg. 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 muscle examined, and EMG signals were recorded telemetrically (Glonner, Biomes 2000). The positions of the electrodes were marked on the skin by small ink tattoos [17]. 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 $3dB^{-1}$) and digitized at the sampling frequency of 1 000 Hz by an on-line computer system. EMG was full wave rectified, integrated (IEMG in $mV \times s$) and time normalized for the maximal peak force phase of the isometric contractions (500–1 500 ms) to calculate maximal IEMG [15].

Anthropometry and muscle cross-sectional area

Height and weight were measured and percentage of body fat was estimated by measuring skin-fold thickness at 4 different sites according to Durnin and Womersley [4]. The muscle cross-sectional area of the right quadriceps femoris (The CSA of QF) was assessed before and after the 21-week experimental training period using magnetic resonance imaging (MRI) (1.5-Tesla, Gyroscan S15, Philips) at the Keski-Suomen Magneettikuvaus Ltd., Jyväskylä, Finland. The length of the femur (Lf), taken as the distance from the bottom of the lateral femoral condyle to the lower corner of the femur head, was measured on a coronal plane. Subsequently, 15 axial scans of the thigh interspaced by a distance of 1/15 Lf were obtained from the level of 1/15 Lf to 15/15 Lf as described previously [17]. Great care was taken to reproduce the same, individual femur length each time using the appropriate anatomical landmarks. All MR images were then

ported to a Macintosh computer for the calculation of muscle CSA. For each axial scan, CSA computation was carried out on the quadriceps femoris as a whole and for the final calculation of the CSA, the mean of slices 5/15–12/15 were used (slice 5 being closer to the knee joint of the thigh). CSA (measured as cm²) was determined by tracing manually along the border of the quadriceps femoris.

Aerobic performance measurements

Maximal oxygen uptake (VO_{2MAX}) test was carried out using the bicycle ergometer (Ergoline Ergometrics 800S, Bitz, Germany) for the SE and E groups. The intensity was 75 W at the beginning of the test and was increased by 25 W every 2nd min until exhaustion. Heart rate (HR) was monitored continuously (S810, Polar Electro, Kempele, Finland) during the test. Blood samples were taken from the fingertip every 2nd min at the end of the each stage, one and three min after the test to measure blood lactate (LA) concentrations (Eppendorf™ Ebio 6666 lactate analyzer, Hamburg, Germany). Oxygen uptake (VO₂) was measured continuously using the SensorMedics® Vmax229 (Palo Alto, CA, USA). The highest 60-s VO₂ value was taken as the VO_{2MAX}. Maximal cycling power (P_{MAX}) was determined as the power when the subject became exhausted and it was calculated as follows: P_{MAX} = power of the last whole completed stage (W) + (cycling time (s) of the power at exhaustion) / 120 (s) × 25 (W). Cycling power of the anaerobic threshold (P_{ANT}) was determined using both lactate and respiratory variables using the same method as Aunola and Rusko [1]. Heart rates corresponding to aerobic and anaerobic thresholds for calculating the right training intensities were determined as described in detail previously [1].

Serum hormone concentrations

Resting venous blood samples (10 ml) were taken after 12 h of fasting in the morning at 0700–0800 h for the determination of serum testosterone (T) and cortisol (Cort) concentrations. The whole blood was centrifuged at 3 500 rpm for 10 min. Serum was removed and frozen at –80 °C until analyzed. Serum testosterone concentrations were measured by the Chiron Diagnostics ACS: 180 automated chemiluminescence system using an ACS: 180 analyzer (Medfield, MA). The sensitivity of the testosterone assay was 0.42 nmol/L, and the intra-assay coefficient of variation was 6.7%. The assays of serum cortisol were carried out by radioimmunoassays using kits from Farnos Diagnostica (Turku, Finland). The sensitivity of the cortisol assay was 0.05 nmol/L, and the intra-assay coefficient of variation was 4.0%. All the assays were carried out according to the instructions of the manufactures. All samples of the test subject were analyzed in the same assay for each hormone.

Statistical methods

Standard statistical methods were used for the calculation of means, standard deviations (sd) and standard errors (se). The data were analyzed utilizing multivariate analysis of variance (MANOVA) with repeated measures (group-by-training interactions) and a 1-way analysis of variance (1-way ANOVA with Bonferroni post hoc-test, differences between the groups). The differences within the groups during the training period were analyzed using the Bonferroni test. When comparing differences between groups in aerobic characteristics (only 2 groups), the Student's t-test was utilized. Relationships between the different performance characteristics were determined by using Pear-

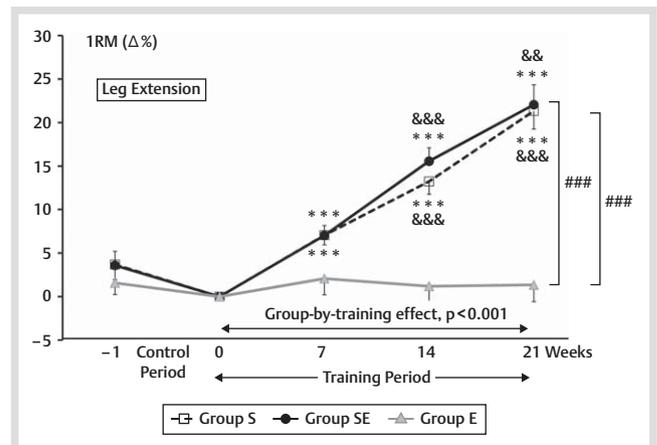


Fig. 1 Relative changes (mean \pm se) in 1RM during the 21-week training period. (***) $p < 0.001$; compared to week 0, && and &&& = $p < 0.01$ and $p < 0.001$; compared to previous time point, ### $p < 0.001$, difference between groups from week 0 to week 21.

son's product-moment correlation coefficient tests. The $p < 0.05$ criterion was used for establishing statistical significance.

Results

Leg extension force

Significant group-by-training effect during the 21-week training period in maximal bilateral concentric force was observed (1RM; $p < 0.001$) (● Fig. 1), with a significantly larger increases in S (1RM by $21 \pm 8\%$, from 189 ± 27 to 228 ± 29 kg, $p < 0.001$) and in SE (1RM by $22 \pm 8\%$, from 171 ± 17 to 209 ± 24 kg, $p < 0.001$) than in E (1RM by $1 \pm 6\%$, from 175 ± 19 to 177 ± 19 kg, ns).

Knee extension force, RFD and maximum EMG

Significant group-by-training effects during the 21-week training period were observed in maximal isometric unilateral knee extension force (F_{KE}) ($p < 0.001$) (● Fig. 2a) and RFD ($p < 0.01$) (● Fig. 3). The increases in isometric F_{KE} in S ($20 \pm 10\%$, from 713 ± 99 to 853 ± 101 N, $p < 0.001$) and in SE ($28 \pm 11\%$, from 680 ± 82 to 865 ± 90 N, $p < 0.001$) were larger than in E ($4 \pm 8\%$, from 710 ± 116 to 731 ± 107 N, ns.) (● Fig. 2a). Similar increases of $32 \pm 40\%$ ($p < 0.05$) and $31 \pm 25\%$ ($p < 0.05$) took place in the maximum iEMG of right VM of the isometric action in S and SE, respectively (● Fig. 2b). In RFD, within groups analyses showed that only S improved RFD of knee extension during 21-week training period ($38 \pm 31\%$, from 7286 ± 2135 to 10017 ± 3774 N/s, $p < 0.05$) and this increase was greater ($p < 0.05$) than in SE ($-7 \pm 51\%$, from 6276 ± 2972 to 5037 ± 2407 N/s, ns.) (● Fig. 3).

Anthropometry and muscle CSA

Body mass did not change significantly during the 21-week training period in any group but the SE group reduced body fat % from $22.5 \pm 4.5\%$ to $20.2 \pm 4.4\%$ ($p < 0.01$) (● Table 1). Significant group-by-training effect ($p < 0.001$) was observed for the muscle CSA of total QF, with a significantly greater magnitude of increase in SE ($11 \pm 5\%$, $p < 0.001$) than in S ($6 \pm 5\%$, $p < 0.001$) and in E ($2 \pm 2\%$, $p < 0.05$) (● Fig. 4). In S a significant correlation was observed between the individual changes in CSA of QF and the changes in 1RM ($r = 0.62$, $p < 0.05$).

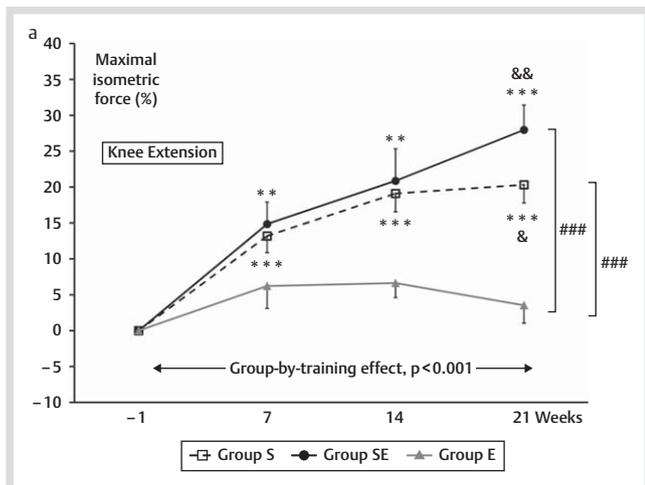


Fig. 2a Relative changes (mean \pm se) in unilateral maximal isometric knee extension force during the 21-week training period. (* p < 0.01, *** p < 0.001; compared to week 0; & p < 0.05, && p < 0.01; compared to week 7, ### p < 0.001; difference between groups from week 0 to week 21).

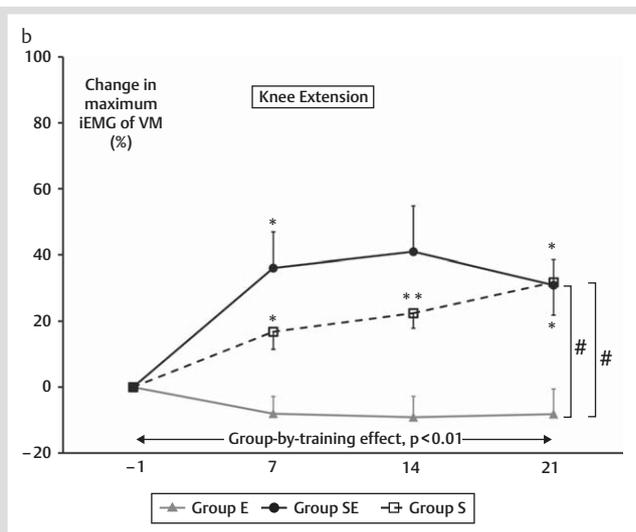


Fig. 2b Relative changes (mean \pm se) in the maximum iEMG of unilateral maximal isometric knee extension force during the 21-week training period. (* p < 0.05, ** p < 0.01; compared to week 0, # p < 0.05; difference between groups from week 0 to week 21).

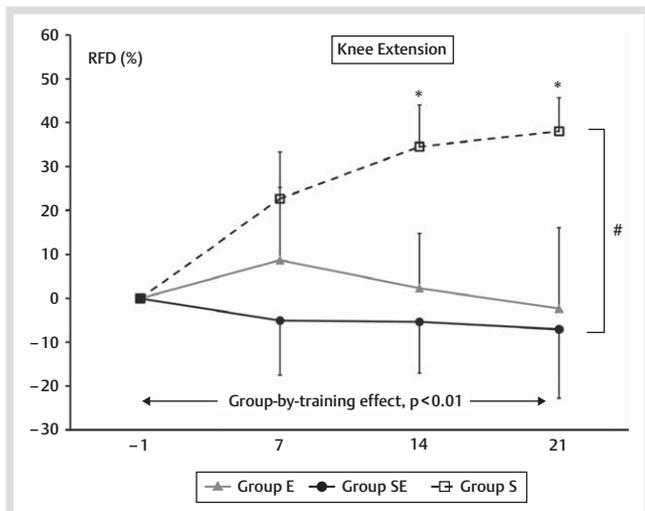


Fig. 3 Relative changes (mean \pm se) in RFD of isometric knee extension action during the 21-week training period. (* p < 0.05; compared to week 0, # p < 0.05, difference between groups from week 0 to week 21, RFD = rate of force development).

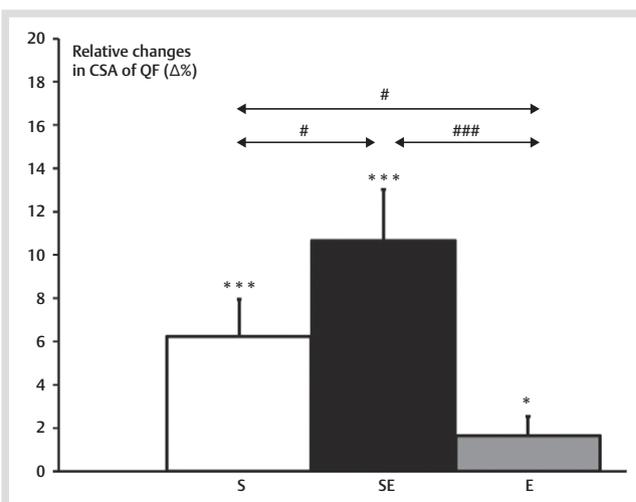


Fig. 4 Relative changes (mean \pm se) in the cross-sectional area (CSA) of m. quadriceps femoris (QF) during the 21-week training period (within group * p < 0.05, *** p < 0.001; between groups # p < 0.05, ### p < 0.001).

Aerobic characteristics

We observed significant group-by-training effect in maximal cycling power (p < 0.05) during 21-week training period with a significantly larger (p < 0.01) improvement for SE ($9 \pm 8\%$) than E ($-1 \pm 5\%$) during the first 7 weeks of training and during the last 7 weeks smaller (p < 0.05) for SE than E (SE: $1 \pm 6\%$ vs E: $7 \pm 3\%$) (● Fig. 5a). During the whole 21-week training period both SE and E increased maximal cycling power by $17 \pm 12\%$ and $11 \pm 6\%$ (p < 0.001), respectively (● Fig. 5a). Also in VO_{2MAX} (both absolute and relative to body weight values) significant group-by-training effect was found (p < 0.01) during the whole 21-week period with a significantly larger increase for SE (l/min: $17 \pm 11\%$, $ml \times kg^{-1} \times min^{-1}$: $19 \pm 11\%$) than in E (l/min: $5 \pm 8\%$, $ml \times kg^{-1} \times min^{-1}$: $5 \pm 10\%$) (● Fig. 5b, ● Table 3). The relative changes in VO_{2MAX} (both absolute and relative to body weight values) were greater (p < 0.01) in SE compared to E also during the first 7

weeks of training. The changes during the 21-week period in relative VO_{2MAX} , HR_{MAX} , LA_{MAX} and P_{ANT} are shown in ● Table 3. Both in E and SE the individual changes in VO_{2MAX} ($ml \times kg^{-1} \times min^{-1}$) correlated with the individual changes in maximal cycling power (0 vs. 21 weeks; E: $r = 0.76$, p < 0.01, SE: $r = 0.90$, p < 0.001). In SE, also the individual changes in CSA of QF correlated with the individual changes in maximal cycling power ($r = 0.79$, p < 0.01).

Serum hormone concentrations

No significant changes were observed in basal serum testosterone or cortisol concentrations in any group during the 21-week training period (● Table 4).

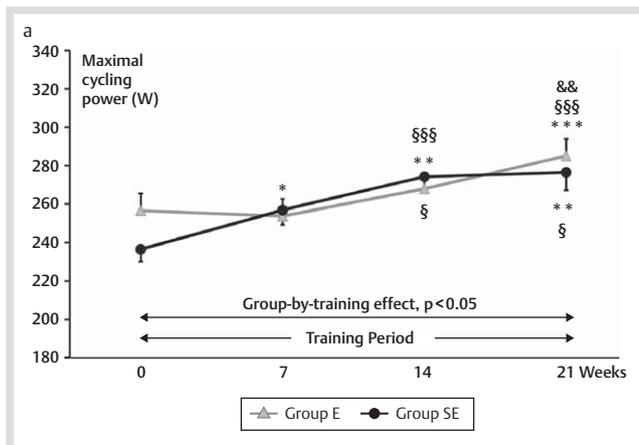


Fig. 5a Changes in maximal cycling power (mean \pm se) in E and SE during the 21-week training period (** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; compared to week 0, §§§ $p < 0.001$, §§ $p < 0.01$, § $p < 0.05$; compared to week 7, && $p < 0.01$, & $p < 0.05$; compared to week 14).

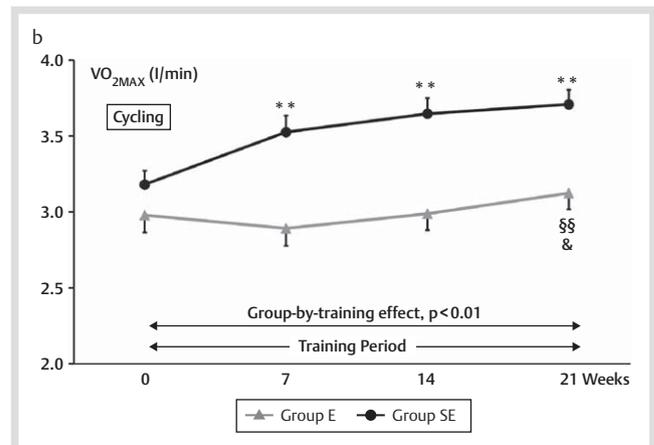


Fig. 5b Changes in absolute maximal oxygen uptake (VO_{2MAX} , mean \pm se) in E and SE during the 21-week training period (** $p < 0.01$; compared to week 0, §§ $p < 0.01$; compared to week 7, & $p < 0.05$; compared to week 14).

Discussion

To our knowledge this is the first study investigating at the same time neuromuscular (e.g. maximal and explosive strength, muscle activation and muscle hypertrophy) and endurance (VO_{2MAX} , maximal and submaximal performance) adaptations that occurs during concurrent strength and endurance training compared to strength and endurance training alone over a prolonged period (21 weeks) in adult sedentary men. Moreover, the present strength training programs included to some extent also rapid muscle action sets of leg exercises to examine the effect of concurrent training on power characteristics of the neuromuscular performance. The main findings of the this study were that prolonged progressive moderate volume concurrent strength/power and endurance training in previously untrained men optimizes the magnitude of muscle hypertrophy, strength and endurance development, whereas interferes with explosive strength gains of unilateral action compared with strength or endurance training alone.

Force characteristics

In the present study maximal forces increased to the same magnitude (20–28%) both in S and SE, indicating no interference effect in maximal strength development during the present concurrent training period. These results are in line with studies of McCarthy et al. [30] and Sale et al. [38] in previously untrained younger subjects. Actually, in the present study maximal forces did improve similarly in S and SE over the whole prolonged 21-week training period, although both volume and intensity of endurance and strength training were increased progressively. This is in line with the study by Sillanpää et al. [39] which included the same kind of 21-week training program in older men. However, Izquierdo et al. [22] observed smaller strength development in SE than S during the last 8 weeks of the 16-week training period. Based on these studies it seems that this difference in strength development observed in the study by Izquierdo et al. [22] was due to too low training stimulus (strength and endurance training only once a week), not interference effect. The present endurance training (mainly by cycling) did not stimulate any force improvements over the 21-week training. This finding is in line with the study by McCarthy et al. [30] and indi-

cates that endurance training alone may not improve force characteristics in healthy adult men but maybe in older subjects with lower initial force levels e.g. [22, 39]. In the present study the increases in isometric knee extension forces were accompanied by the significant increases in voluntary maximal muscle activation (EMG of VM) both in S and SE with no significant difference between the 2 groups. These findings are line with the study of McCarthy et al. [31] indicating that concurrent training does not interfere with neural adaptations to strength training compared to strength training alone.

Although maximal forces increased similarly in S and SE during the 21-week training period, only S improved RFD in the unilateral isometric knee extension action and these changes in RFD differed between S and SE. Thus, this indicates that even a moderate volume concurrent strength and endurance training lead to interference in development of rapid force production not only multijoint bilateral [16] but also more isolated unilateral isometric action compared to strength training alone. This interference effect could not be avoided, even though the present concurrent training program included also high velocity resistance training. This finding is in line with the study by Dudley and Djamil [3] who observed interference in angle-specific maximal isokinetic torque at fast contraction velocities but not at slow contraction velocities. However, Izquierdo et al. [22] showed that also the concurrent training group enhanced leg power (squat exercise, load 60% of 1RM). The differences in these results may be explained by the fact that in the study of Izquierdo et al. [22] the SE group trained endurance only once a week which was “low enough” not to cause interference in power production. In addition, the differences in the nature of rapid force production testing (isometric vs. dynamic action) may lead to somewhat different adaptations. Moreover, the velocity in power testing with a load as high as 60% of 1RM [22] may be too low to detect the possible interference in high contraction velocities.

Muscle hypertrophy

The magnitudes of the increases of CSA of QF in the present study (in S 6%, in SE 11%) were similar in SE and less in S than in the previous studies by Sale et al. [38] (22 weeks, 3 times a week training) and McCarthy et al. [31] (10 weeks, 3 times a week

Table 3 Selected variables in cycle ergometer test in E and SE during the 21-week training period.

Week	Group E				Group SE			
	VO _{2MAX} ml × kg ⁻¹ × min ⁻¹	HR _{MAX} bpm	LA _{MAX} mmol × l ⁻¹	P _{ANT} W	VO _{2MAX} ml × kg ⁻¹ × min ⁻¹	HR _{MAX} bpm	LA _{MAX} mmol × l ⁻¹	P _{ANT} W
0	37.8 ± 4.8	188 ± 9	13.7 ± 1.9 ‡	182 ± 26	36.6 ± 6.0	191 ± 8	11.6 ± 1.7	173 ± 13
7	36.6 ± 3.7	189 ± 11	14.0 ± 2.1	178 ± 23	40.5 ± 5.7**	189 ± 10	11.6 ± 1.5	185 ± 16*
14	37.8 ± 4.3	187 ± 12	14.6 ± 1.6*	194 ± 24 †	41.9 ± 6.2**	189 ± 11	12.6 ± 1.7	198 ± 17**,* † †
21	39.4 ± 3.9 † †	187 ± 12	15.2 ± 2.2*, †	203 ± 24*, † † †	43.3 ± 7.3**	189 ± 12	13.0 ± 1.5	201 ± 23*

Note: Values are means ± sd. VO_{2MAX} = maximal oxygen uptake, HR_{MAX} = maximal heart rate, LA_{MAX} = lactate concentration, P_{ANT} = cycling power at anaerobic threshold.

**p < 0.01 and *p < 0.05; compared to 0, † † † p < 0.001, † † p < 0.01 and † p < 0.05; compared to 7, ‡ = p < 0.05; difference between the groups

Table 4 Serum concentrations of testosterone and cortisol of the different training groups during the 21-week training period.

Week	Group E		Group SE		Group S	
	Testosterone nmol/l	Cortisol μmol/l	Testosterone nmol/l	Cortisol μmol/l	Testosterone nmol/l	Cortisol μmol/l
0	18.7 ± 3.4	0.56 ± 0.13	20.7 ± 7.7	0.50 ± 0.16	22.1 ± 6.2	0.43 ± 0.11
7	18.1 ± 4.2	0.50 ± 0.14	23.2 ± 4.7	0.40 ± 0.11	21.7 ± 6.1	0.48 ± 0.12
14	18.0 ± 3.4	0.54 ± 0.15	19.5 ± 5.5	0.38 ± 0.10	22.1 ± 7.7	0.46 ± 0.13
21	17.8 ± 3.7	0.50 ± 0.08	21.5 ± 4.5	0.45 ± 0.12	20.2 ± 7.4	0.46 ± 0.11

Note: Values are means ± sd

training), who observed leg extensor hypertrophy of 11–14% both in S and SE. Thus, it seems that the frequency of 2 times a week strength training alone is not enough to reach the same level hypertrophic adaptations as training 3 times a week. However, it must be taken into account that in the present study we used a different methodology to measure CSA (MRI vs. computerized tomography). In addition, in the present study the increases in CSA of QF differed between the groups indicating that endurance training had induced some additional stimulus to promote hypertrophy when training 2 times a week each training mode. Indeed, the changes in CSA of QF in E suggest that even endurance training alone, when performed by cycling, leads to small (but significant) hypertrophy (by 2%) of the trained muscles. This is in agreement with McCarthy et al. [31] and Sillanpää et al. [39] who also reported small increases in leg muscle CSA in the cycling endurance training group. One reason for this may be that moderate average force levels produced by cycling action are high enough and the time of the each pedal push is long enough to induce some stimulus to hypertrophic adaptations in previously untrained men. However, the present degree of hypertrophy in E remained so minor that no significant increases in strength took place in E. The observation of maintained body mass with decreased fat in SE is in line with the fact that the SE group increased also muscle mass (CSA of QF) to a greatest degree.

Endurance characteristics

It has been previously shown that concurrent training induced similar increases in maximal cycling power [22] or VO_{2MAX} in cycling [3,30,38] as endurance training alone in previously untrained men. The present findings (cycling power increased by 17% and 11% in SE and E during the 21-week period) support the observation of Izquierdo et al. [22]. However, a significant increase in VO_{2MAX} (by 17%) was found only in SE during the 21-week period. Overall, it seems that the present concurrent training led to greater improvements in VO_{2MAX} (both absolute and relative values, SE: 17–19% vs. E: ~5%, p < 0.01) and maximal cycling power than endurance training alone, although the difference between the changes was significant only in VO_{2MAX}.

Thus, the addition of strength training to endurance training in previously untrained men may contribute positively to the changes even in VO_{2MAX} and endurance performance measured by the cycling action compared to endurance training alone, when the overall training volumes were moderate. This may also indicate that neuromuscular characteristics limit the utilization of “real” VO_{2MAX} and/or endurance performance [35,36] also in cycling in sedentary men. In addition, the individual changes in maximal cycling power correlated to changes in CSA of QF (r = 0.79, p < 0.01) in the SE group indicating some contribution of neuromuscular factors to the development in endurance performance. However, the correlations between the individual changes in maximal cycling power and changes in VO_{2MAX} were strong in both SE (r = 0.87, p < 0.001) and E (r = 0.76, p < 0.01). Interestingly, the time course of development in maximal cycling power and VO_{2MAX} differed between SE and E. During the first, low volume and intensity 7-week training period only the SE group improved aerobic characteristics (maximal cycling power and power at anaerobic threshold, VO_{2MAX}) and the changes differed between SE and E. This may indicate that the first 7-week endurance training stimulus twice a week was too low even in the present untrained subjects, but the addition of 2 strength training sessions induced additional stimulus also for gains in endurance characteristics. Unfortunately, we did not measure aerobic characteristics in S but it has been shown that strength training alone may induce at least minor improvements in VO_{2MAX} [10,30], performance economy [28] and maximal performance [21,29] measured by cycling in previously untrained subjects. However, the mechanism by which resistance training may increase VO_{2MAX} is somewhat unclear. On the other hand, we observed differences in the changes in maximal cycling power (SE: 1% vs. E: 7%) during the final and most intense 7 training weeks between SE and E. This may be due to a slight interference effect in SE or E had simply more room to develop their aerobic characteristics because of the lower improvements during the first 7-week period.

One possible reason for the “unexpected” VO_{2MAX} development especially during the first 7 weeks of the training period in E is the variability of the individual training responses to endurance

(as well as to resistance) training. Several studies have shown that individuals may adapt differently after exposure to very similar training loads [2,10,24]. For example, mean improvements in VO_{2MAX} following standardized endurance training often fall within 10–15% of baseline values, but in the same time individual responses have been shown to range from negative values to over 40% improvement [2]. It is possible that these individual differences in VO_{2MAX} development may affect the present results because of relatively small subject number ($n=11$ both in E and SE). In addition, we should remember that subjects carried out approximately half of the endurance training by themselves (not supervised). This might have caused some differences in the actual training intensity contributing to the adaptations of the training although subjects were carefully instructed how to carry out the training.

Basal hormones

The basal hormonal levels did not change significantly during the present 21-week training period in any of the groups. This observation indicates that either strength or endurance training alone or even when combining these training modes and doubling the frequency of training did not lead to a change in the catabolic hormonal environment. It has been suggested that high volume-related overtraining increases basal cortisol and decreases basal testosterone levels [5,18]. Thus, it seemed that the volume of training used in the present study was not associated with endocrinological overtraining symptoms in SE. This is in line with the observations of the systematic increase in maximal force and leg muscle hypertrophy over the entire training period of 21 weeks. However, great care should be exercised with the interpretation of the data and not to oversimplify these hormonal results as indicators of the anabolic/catabolic state.

Summary

Overall, this study using the present moderate volume of training did not support the chronic strength interference hypothesis due to concurrent training, because both maximal forces and muscle mass (CSA of QF) increased similarly or even to a greater extent in SE than in S. In contrast, this study suggests that a moderate intensity and training volume may lead to synergistic effects of combined strength and endurance cycling training promoting positive endurance and neuromuscular gains in previously untrained men. However, our results also showed that interference in rapid force production may occur, when training was performed concurrently, even though explosive type of exercise was also included as a part of the present strength training program. In conclusion, it seems that a sufficient frequency to optimize both strength and endurance enhancement in previously sedentary individuals is to train 2 times a week in both strength and endurance with progressively increasing volume and intensity at least over a 21-week time period. Further studies should be conducted to ascertain whether muscle strength and endurance performance were compromised, if a given threshold volume is surpassed or drastically reduced especially when both strength and aerobic endurance need to be concurrently enhanced.

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