

# Concurrent Endurance and Explosive Type Strength Training Improves Neuromuscular and Anaerobic Characteristics in Young Distance Runners

## Authors

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## Key words

- postpubertal endurance athlete
- rapid force production
- cardiovascular adaptation
- neural adaptation

## Abstract

To study effects of concurrent explosive strength and endurance training on aerobic and anaerobic performance and neuromuscular characteristics, 13 experimental (E) and 12 control (C) young (16–18 years) distance runners trained for eight weeks with the same total training volume but 19% of the endurance training in E was replaced by explosive training. Maximal speed of maximal anaerobic running test and 30-m speed improved in E by  $3.0 \pm 2.0\%$  ( $p < 0.01$ ) and by  $1.1 \pm 1.3\%$  ( $p < 0.05$ ), respectively. Maximal speed of aerobic running test, maximal oxygen uptake and running economy remained unchanged in both

groups. Concentric and isometric leg extension forces increased in E but not in C. E also improved ( $p < 0.05$ ) force-time characteristics accompanied by increased ( $p < 0.05$ ) rapid neural activation of the muscles. The thickness of quadriceps femoris increased in E by  $3.9 \pm 4.7\%$  ( $p < 0.01$ ) and in C by  $1.9 \pm 2.0\%$  ( $p < 0.05$ ). The concurrent explosive strength and endurance training improved anaerobic and selective neuromuscular performance characteristics in young distance runners without decreases in aerobic capacity, although almost 20% of the total training volume was replaced by explosive strength training for eight weeks. The neuromuscular improvements could be explained primarily by neural adaptations.

## Introduction

It has been traditionally suggested that endurance performance, such as distance running, is determined by maximal oxygen uptake ( $\dot{V}O_{2max}$ ), fractional utilization of  $\dot{V}O_{2max}$  and running economy [3]. Athletes with similar  $\dot{V}O_{2max}$  may have different running economy and endurance running performance can vary considerably [7, 27]. There is also evidence that anaerobic work capacity may influence considerably running performance in well-trained distance runners [6]. In addition, Noakes [25] has suggested that in elite athletes muscle power factors affected by an interaction of neuromuscular and anaerobic characteristics may limit endurance performance and may be better predictors of success than  $\dot{V}O_{2max}$ . Thus, it might be beneficial also for endurance runners to improve their neuromuscular and anaerobic characteristics.

Specific explosive type strength training (with low load but high action velocities) leads mainly to neural adaptations (e.g. increased rate of neural activation of motor units) where as muscle hypertrophy will remain smaller than during typi-

cal heavy resistance training [14,16,31]. This might be beneficial for distance running performance, since an increased body mass is not desirable as athletes need to transport this higher body mass. Some recent studies [32,33] have also demonstrated benefits of plyometric training on distance running performance. It has been shown that strength/plyometric training improves running economy in runners [19,22,27,32,33], although the exact mechanism why this occurs is still unclear. It has been suggested that plyometric training improves musculotendinous stiffness resulting in better running economy and performance, because more stiff muscles are able to store and utilize elastic energy better during the ground contact [32]. On the contrary, Turner et al. [33] did not find any improvements in capabilities that would have indicated improved ability to store and utilize elastic energy. Paavola et al. [27] postulated that explosive strength training had a positive influence on running economy and running performance due to improved neuromuscular characteristics in endurance athletes. However, it has been suggested that concurrent endurance and strength training

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**Table 1** Physical characteristics of the experimental and control groups before and after the 8-week training period

Variables	Experimental group (n = 9♂ + 4♀)		Control group (n = 9♂ + 3♀)	
	Before	After	Before	After
Age, year	17.3 ± 0.9		17.3 ± 0.5	
Height, cm	177.4 ± 7.6	177.4 ± 7.4	171.7 ± 7.3	171.9 ± 7.1
Body weight, kg	63.0 ± 6.0	64.1 ± 6.1**	60.2 ± 7.5	60.8 ± 7.6
Fat, %	13.1 ± 6.8	13.7 ± 7.4	12.2 ± 3.5	12.4 ± 3.4
Lean body mass, kg	55.1 ± 8.5	55.6 ± 8.9	52.9 ± 7.5	53.4 ± 7.6
Thigh girth, cm	52.9 ± 2.7	53.7 ± 2.8*	51.6 ± 2.1	52.6 ± 1.5*
Calf girth, cm	35.4 ± 1.9	35.8 ± 2.1**	35.2 ± 1.6	35.5 ± 1.7
Thickness of the QF, cm	2.25 ± 0.28	2.35 ± 0.29**	2.07 ± 0.31	2.10 ± 0.31*

Values are means ± SD. Significant difference between before and after the training period (\*  $p < 0.05$ , \*\*  $p < 0.01$ ). QF = m. quadriceps femoris, ♂ = male, ♀ = female

might interfere or inhibit strength and/or power development, at least, if the concurrent training period is too long and/or the training volume or intensity is too high [3, 8, 11, 13, 20, 21].

Nowadays many young, especially postpubertal, athletes are being encouraged to train intensively for sport competitions. Fournier et al. [10] showed that postpubescent (age 16–17) males could increase their glycolytic enzyme activity during a 3-month sprint training period. With regard to strength training male and female adolescents can obtain substantial strength gains through systematic resistance training [24]. Häkkinen et al. [17] suggested that postpubescent weightlifters (age 17) would show similar strength training adaptations compared to adults. Aerobic capacity regarding  $\dot{V}O_{2\max}$  increases with age and due to training through 15–20 years of age in endurance athletes [28], indicating high trainability at that age group. It seems that adolescents are less efficient in energy expenditure in weight-bearing activity (e.g. running) compared to adults, but adolescents improve their economy with increasing age. Thus, compared to adult athletes, less information is available about the physiological trainability of postpubertal athletes. However, it has been suggested that improvements in performance characteristics in young athletes are strongly related both to their biological maturation and to training [24] but it is not known to what extent the concurrent explosive strength and endurance training adaptations differ in young, but postpubertal athletes from those observed in adult athletes.

There are only a few studies which have investigated hormonal adaptations to concurrent strength and endurance training. Bell et al. [4] reported no changes in basal concentrations of testosterone, growth hormone or SHBG (sex hormone binding globulin) after 12 weeks of concurrent training in physically active male and female students. Interestingly, greater urinary cortisol was observed in women after concurrent training but not in men. Kraemer et al. [20] showed a substantial increase in exercise-induced cortisol concentration following a 12-week period of high volume concurrent strength and endurance training in physically active soldiers. These results indicate that the possible interference effect in strength development after too intensive concurrent training may be at least partly due to overtraining which leads to more catabolic hormonal responses. However, it is not known how the hormonal environment changes due to concurrent strength and endurance training in young, but postpubertal athletes and how these possible changes affect their trainability.

The purpose of this study was to investigate the effects of concurrent explosive type strength and endurance training on neu-

romuscular, anaerobic and endurance performance in young distance runners. In addition, our purpose was to examine possible changes in basal levels of serum hormones after concurrent training in young endurance athletes and their possible relationship with changes in performance characteristics.

## Methods

### Subjects

Eighteen males and seven females volunteered to participate in this study. All subjects were young (age between 16–18 years), postpubertal distance runners. The athletes had at least two years of training experience in distance running and most of the subjects were studying in the same sport high school. Physical characteristics of the subject groups are presented in **Table 1**. The subjects and their parents 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. Subjects were not on any medications that would affect physical performance. Due to technical problems in the testing situation the number of the subjects who could carry out isometric leg press test was ten in group E. The study was approved by the Ethics Committee of the University of Jyväskylä, Finland.

### Experimental design

The subjects were tested before and after the training period of eight weeks using the identical two-day-measurement protocols (**Table 2**). The subjects were assigned to either experimental (9 males and 4 females) or control group (9 males and 3 females). The experimental group (E) trained for 8 weeks endurance and explosive type strength training. The control group (C) did not change their usual endurance training during the eight-week period. The present study was carried out in the spring before the competition season.

### Training

The total absolute volume of training was the same in both groups (E group 8.8 ± 2.1 h and 12.4 ± 3.0 times/week, C group 8.5 ± 2.5 h and 9.3 ± 1.0 times/week) but 19% of the endurance training hours in the E group were replaced by explosive type strength training consisting of general and sport-specific exercises. This kind of explosive training was carried out 3 times a week. The rest of the training was “traditional” endurance training (71% of the total training hours) or supplementary training

**Table 2** The two-day-measurement protocol

Day 1	isometric trunk forces, CMJ, 5B-test	recovery (30 min)	MART	recovery (180 min)	ultra sound measurement of the QF
Day 2	30 meter running speed test	recovery (60 min)	dynamometer test for the leg extensors	recovery (120 min)	VO <sub>2</sub> -test on the treadmill

such as co-ordination training, circuit training, ball games etc. The C group did not make any changes in their training program during the 8-week period (only 4% of the total training hours included explosive type strength training, 82% was endurance training and the rest was supplementary training).

The present explosive training sessions consisted of sprinting, jumping and strength training exercises. Each session was performed on an average once a week. Explosive training sessions lasted 30–60 minutes. Training sessions consisted of various running sprints (5–10) × (30–150 meters) and jumping exercises (alternative jumps, calf jumps, squat jumps, hurdle jumps) without external load or gym exercises (with low loads) such as half squats, knee extensions, knee flexions, calf raises, abdominal curls, back extensions (2–3 sets/movement and 6–10 repetitions/set). The main training principle during the eight week explosive strength training period was to train with low loads but high action velocities. The “traditional” endurance training was mainly running. The subjects were asked to keep written records of their training throughout the training period. Most of their endurance training (>95% in both groups) took place below the anaerobic threshold, which was determined in the aerobic performance test on treadmill before the training period [2].

### Muscle strength measurements

The subjects were familiarized with the testing procedures of voluntary force production of the muscle groups tested. 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 and maximal isometric force of the bilateral leg extensor muscles (hip, knee and ankle extensors) were measured using an electromechanical leg press dynamometer (modified David 210, David Industries Ltd, Outokumpu, Finland). In this test the subjects were in a sitting position so that the knee and hip angles were 107 and 110 degrees, respectively. The subjects were instructed to exert their maximal force as fast as possible during a period of 2.0–3.0 s. A minimum of three trials was completed for each subject and the best trial with regard to maximal peak force was used for the subsequent statistical analysis.

The force signal was recorded by a computer (Toshiba T3200) by using an AT Cudas A/D converter card and then analyzed with a Cudas TM computer system (Dataq Instruments, Inc., OH, USA). Maximal peak force ( $F_{ISOM}$ ) was defined as the highest value of the force (N) recorded during the bilateral isometric leg extension. The force-time analysis on the absolute scale included the calculation of average time (ms) to reach force levels of 100 N, 250 N, 500 N, 750 N, 1000 N and 1500 N from the start of the contraction. The maximal rate of force development (RFD) ( $N \cdot s^{-1}$ ) was also analyzed and defined as the greatest increase in force in a given 50 ms time period [15].

A David 210 dynamometer (David Industries Ltd) was also used to measure maximal bilateral concentric force production of the

leg extensors (hip, knee and ankle extensors) [15]. The subject was in a seated position so that the hip angle was 110 degrees. On verbal command the subject performed a concentric leg extension starting from a flexed position of 70 degrees of the knee angles trying to reach a full extension of 180 degrees against the resistance determined by the loads (kg) chosen on the weight stack. In the testing of the maximal load, separate 1 RM (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 1 RM. This dynamic testing action was used in addition to that of the isometric one, since the training was also dynamic in nature.

### EMG measurements

Electromyographic (EMG) activity during the bilateral extension of the leg extensors was recorded from the agonist m. vastus lateralis (VL), m. vastus medialis (VM) and m. rectus femoris (RF) of the right leg. Bipolar (20 mm inter electrode distance) surface EMG recording (miniature-sized skin electrodes, Sensormedics 650414, Anaheim, CA, USA) was employed. The electrodes were placed longitudinally on the motor point areas of the muscles examined, and EMG signals were recorded telemetrically (Telemyo 16, Glonner-Electronics, Krailling, Germany). The positions of the electrodes were marked on the skin by small ink tattoos. These dots ensured the same electrode positioning in each test over the 8-week experimental period. The EMG signal was amplified (by a multiplication factor of 200; low pass cut off frequency of 360 Hz 3 dB<sup>-1</sup>) and digitized at the 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 period of the first 100 and 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 [15].

### Maximal anaerobic running test

The subjects performed maximal anaerobic running test (MART, modified from treadmill version, 30, 26), which consisted of series [9–10] of 150-meter runs on an indoor track with a 100-second recovery between the runs. A running start of 5 meter was used for each 150-m run. The velocity of the first 150-meter run was 3.94 m·s<sup>-1</sup> (females) or 4.75 m·s<sup>-1</sup> (males) and thereafter the velocity was increased by 0.41 m·s<sup>-1</sup> for each consecutive run. The subjects were guided during the eight or nine 150-meter runs to the desired running velocity by the so called light rabbit (Protom, Naakka, Finland). The last 150-meter run was performed at runner's maximal effort. Before the test, 40 seconds after each run and 2.5 and 5 minutes after the last run fingertip blood samples were taken and lactate concentration was analyzed using Eppendorf<sup>TM</sup> Ebio 6666 lactate analyzer (Eppendorf-Netheler-Hinz, Hamburg, Germany). The maximal mean velocity of MART ( $V_{MART}$ ) was calculated from the fastest 150-m

run. The velocity associated with 3, 5, 7 and 10 mmol·l<sup>-1</sup> blood lactate levels ( $V_3$ ,  $V_5$ ,  $V_7$  and  $V_{10}$ , respectively) were determined from the blood lactate vs. velocity curve by linear extrapolation from the two consecutive lactate values which were above and below the desired value [26].

### Thirty-meter running speed and jump-tests

On the second day the athletes performed a 30-meter running test on an indoor track. After warm-up the subjects performed three times the maximal action with a running start of 20 meters. The average maximal speed ( $V_{30}$ ) was calculated from the best running time which was measured by two photocell gates (New Test, Kempele, Finland). The 5-jump test (5J) started from a standing position, and the subjects tried to cover the longest distance by performing a series of five forward jumps with alternative right- and left-leg contacts [27]. Three to five trials was completed for each subject and the distance of the 5J was measured with a tape. The counter movement jump (CMJ) was performed on a special jump mat (New Test, Kempele, Finland) and subjects were instructed to jump for maximal vertical jump keeping their hand placed on their hips during the jump. No restrictions were placed on the knee angle during the eccentric phase of the jump [32]. Subjects completed three to five jumps and the best jump height was recorded for analysis.

### Aerobic performance

The maximal oxygen uptake ( $\dot{V}O_{2\max}$ ) and maximal endurance performance ( $V_{\text{END}}$ ) were determined during running on a treadmill at the end of the second day. The velocity was 8 km·h<sup>-1</sup> (females) or 10 km·h<sup>-1</sup> (males) in the beginning of the test and was increased by 2 km·h<sup>-1</sup> after first three minute step and after that 1 km·h<sup>-1</sup> every third minute until exhaustion. The inclination was constant 1 degree during the whole test. Heart rate was monitored continuously during the test. The oxygen consumption was measured continuously for every 20 seconds using the SensorMedics® Vmax229 or the SensorMedics® 2900Z gas analyzer (the mixing chamber method). Blood samples were taken from fingertip every 3rd min to measure blood lactate concentrations and the treadmill was stopped about 15–30 seconds. Blood lactate was determined using Eppendorf™ Ebio 6666 lactate analyzer. The  $\dot{V}O_{2\max}$  was taken as the highest 60-s  $\dot{V}O_2$  value. The maximal endurance performance was determined as the treadmill velocity ( $V_{\text{END}}$ ) when the subject was exhausted and it was calculated as follows:  $V_{\text{END}} = \text{speed of the last whole completed speed (km·h}^{-1}\text{)} + (\text{running time (s) of the speed when exhausted} - 30 \text{ seconds}) / (180 - 30 \text{ seconds}) \cdot 1 \text{ km·h}^{-1}$ . Since the running economy is defined as the O<sub>2</sub> demand for a constant velocity [7], the running economy was determined by averaging the oxygen consumption for the last minute at the velocities of 10, 12, 13 and 14 km·h<sup>-1</sup>.

### Anthropometry

Body mass and standing height were measured. The fat percentage (fat%) was estimated by measuring skin-fold thickness at four different sites according to Durnin and Womersley [9]. Fat-free mass (FFM) was calculated throughout body mass and fat% as follows:  $\text{FFM} = (100 - \text{fat}\%) \cdot \text{body mass} / 100$ .

The right calf and thigh girths were measured with a tape applied around the relaxed muscles. The thickness of the thigh muscles was measured at three points in m. quadriceps femoris (QF) (m. vastus lateralis, m. vastus medialis and m. rectus femoris) using ultrasound muscle thickness measurements [23]. The

muscle thickness was measured with a compound ultrasonic scanner (SSD-190, Aloka Fansonic, Tokyo, Japan) and a 5-MHZ convex transducer. The measuring sites at each muscle were precisely located on the anterior surface at 50% of the thigh length (the distance between from the greater trochanter of the femur to the articular cleft between the femur and tibia condyles). The value used as thickness of QF was calculated as the average of each three measuring points.

### Resting blood samples

Blood samples were taken after 12 hours of fasting in the morning of the first measurement day at 0700–0800 hours for the determination of serum testosterone (T), free testosterone (FT) and cortisol (C) concentrations for the males. Ten milliliters blood was drawn for the hormonal measurements. The whole blood was centrifuged at 3500 rpm for ten minutes. Serum was removed and frozen at –80°C until analyzed. The hormones were determined using Labsystems i EMS Reader MF (Finland). The concentrations T and FT were measured in duplicate by ELISA using kits from IBL (Hamburg, Germany). The sensitivity of T and FT assays were 0.083 ng·ml<sup>-1</sup> and 0.17 pg·ml<sup>-1</sup>, respectively. The intra-assay coefficient of variations (CV) of T and FT were 3.4% and 3.8%, respectively. The assays of serum C concentrations were carried out in duplicate by cortisol immunoassay using kits from R&D Systems (United Kingdom). The sensitivity of the C assay was lesser than 56.7 pg·ml<sup>-1</sup> and the intra-assay CV was 3.9%. All the assays were carried out according to instructions of the manufactures. All samples of the test subject were analyzed in the same assay for each hormone.

### Statistical methods

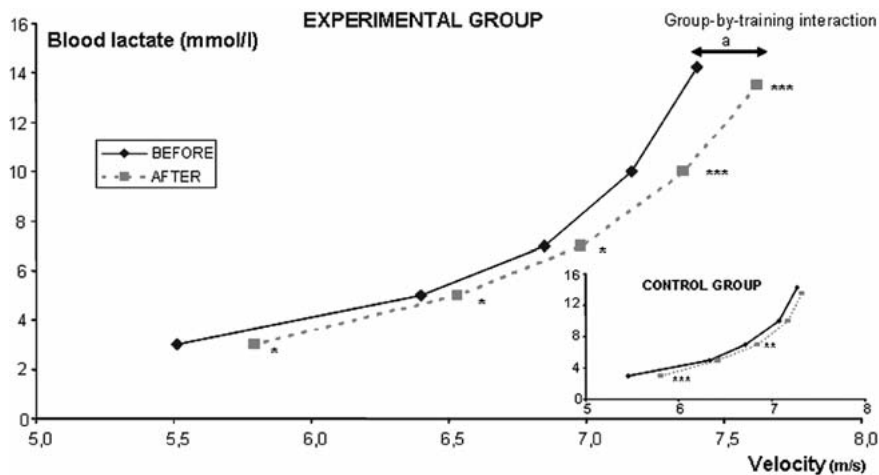
Standard statistical methods were used for the calculation of means, standard deviations (SD), standard errors (SE), and Pearson product moment correlation coefficients. The data were then analyzed utilizing multivariate analysis of variance (MANOVA) with repeated measures (group-by-training interactions). Differences within the groups from pre- to post-test were analyzed using paired Student's *t*-tests. Differences between the mean values between the experimental group and control group before and after the training period were tested by *t*-test (unpaired). Also the differences in the relative (percentage, %) changes during the training period between the groups were tested by *t*-test (unpaired). The  $p < 0.05$  criterion was used for establishing statistical significance.

## Results

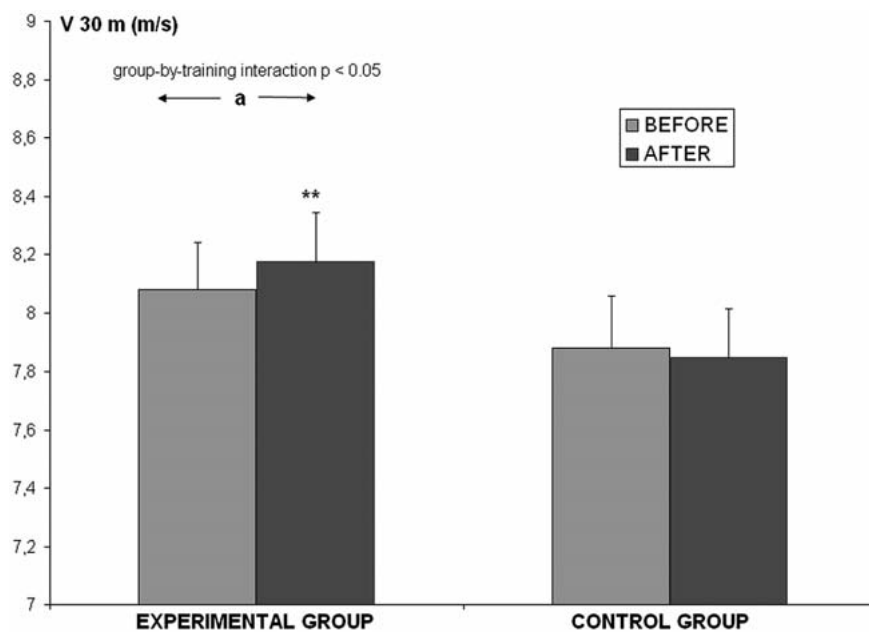


### Maximal anaerobic running test and 30 m speed

$V_{\text{MART}}$ , submaximal velocities in MART ( $V_{10}$ ,  $V_7$ ,  $V_5$ ,  $V_3$ ) and  $V_{30}$  did not differ between the groups before the experiment. After the training period significant group-by-training interaction was found for  $V_{\text{MART}}$  ( $p < 0.01$ ) and  $V_{30}$  ( $p < 0.05$ ) (● Figs. 1 and 2). All the velocities ( $V_{\text{MART}}$ ,  $V_{10}$ ,  $V_7$ ,  $V_5$ ,  $V_3$  and  $V_{30}$ ) increased in E ( $p < 0.001 - 0.05$ ) (● Figs. 1 and 2). In C, only  $V_7$  and  $V_3$  improved significantly ( $p < 0.01 - 0.001$ ) (● Fig. 1). The relative (%) changes in  $V_{\text{MART}}$  ( $p < 0.01$ ) and  $V_{30}$  ( $p < 0.05$ ) also differed significantly between the groups.



**Fig. 1** Running velocity-blood lactate curve of the maximal anaerobic running test (MART) before and after the 8-week training period in the experimental (big scale) and control (small scale) group (a =  $p < 0.05$ , group-by-training interaction at maximal velocity, \*  $p < 0.05$ , \*\*  $p < 0.01$ , \*\*\*  $p < 0.001$ , before vs. after 8-weeks of training).



**Fig. 2** Maximal velocity (mean  $\pm$  SD) of the 30 m speed test in the experimental (E) and control (C) group before and after the 8-week training period (a =  $p < 0.05$ , group-by-training interaction, \*\*  $p < 0.01$ , before vs. after 8-weeks of training).

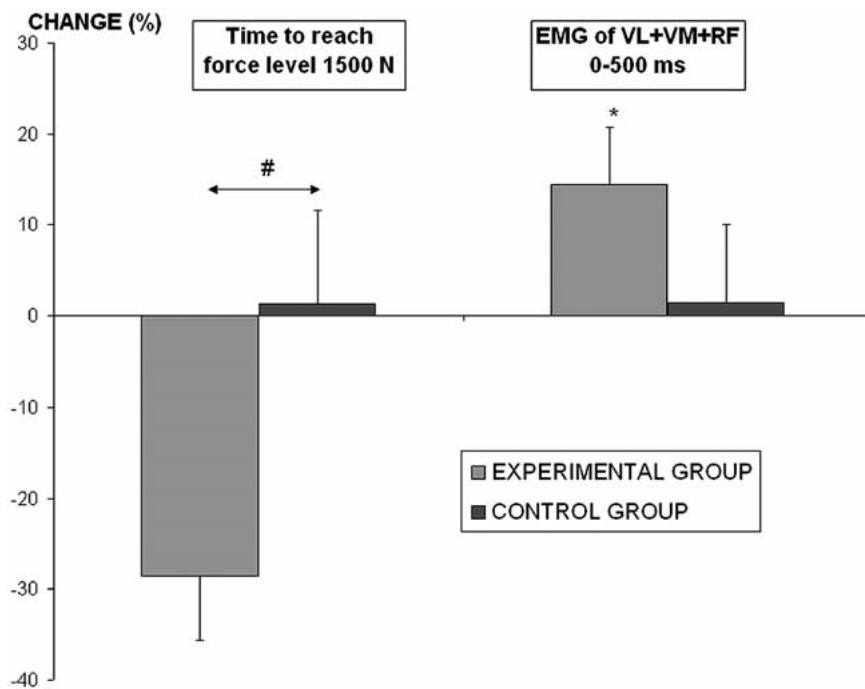
### Maximal forces, force-time curve, EMG and jumping actions

$F_{ISOM}$  and 1RM of leg extensors increased significantly in E by  $8 \pm 9\%$  ( $p < 0.05$ ) and  $4 \pm 5\%$  ( $p < 0.05$ ) but not in C ( $3 \pm 18\%$  and  $4 \pm 12\%$ ), respectively. No significant changes occurred in the maximum IEMG of the VL or VM in E or C. Isometric force-time curve of the leg extensors changed in E so that the times to reach force levels 1000 N ( $-18 \pm 26\%$ ,  $p = 0.06$ ) and 1500 N ( $-29 \pm 22\%$ ,  $p < 0.05$ ) tended to shorten, while in C the times did not change. Also the relative (%) change during the training period in time to reach 1500 N differed between the groups ( $p < 0.05$ ) (● Fig. 3). Correspondingly, RFD of the isometric action increased in E ( $31 \pm 42\%$ ,  $p < 0.05$ ), but not in C (● Fig. 4). These changes in rapid force production were accompanied by the increase of  $14 \pm 19\%$  ( $p < 0.05$ ) in IEMG (average for VL+VM+RF) during the early portion (0–500 ms) of the isometric action (● Fig. 3). There were no significant changes in IEMG or force-time variables in C. The C group impaired the 5J performance by  $1 \pm 2\%$  ( $p < 0.05$ ), but there were no significant changes in 5J in E or in CMJ in E or C.

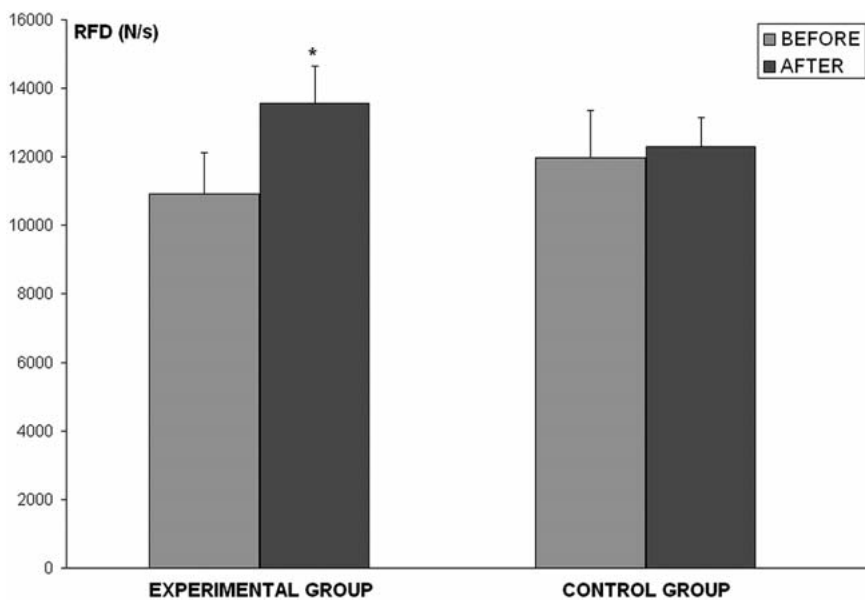
The correlation analysis in E showed that the changes in the  $F_{ISOM}$  correlated significantly with the changes in 1 RM ( $r = 0.63$ ,  $p < 0.05$ ). The changes in the  $F_{ISOM}$  correlated with the changes in maximum (500–1500 ms) IEMG expressed as a sum of VL+VM ( $r = 0.72$ ,  $p < 0.05$ ) and VL+VM+RF ( $r = 0.71$ ,  $p < 0.05$ ) in isometric action in E. The changes in early (0–100 ms) IEMG of VL correlated with the changes in time to reach 1000 N force level ( $r = -0.73$ ,  $p < 0.05$ ) in E (times to reach force level 1000 N varied between 109–145 ms). Correspondingly, the changes in the IEMG of VL+VM (0–500 ms) correlated with the changes in time to reach 1500 N force level ( $r = -0.74$ ,  $p < 0.05$ ) (● Fig. 5) (times to reach force level 1500 N varied between 229–366 ms).

### Aerobic characteristics

There were no significant differences in any aerobic performance variables between the groups before the training period. During the training period neither  $\dot{V}O_{2max}$  nor  $V_{END}$  changed significantly in E or C on the treadmill test (● Table 3). A significant group-by-training interaction ( $p < 0.05$ ) was found in running economy at  $14 \text{ km} \cdot \text{h}^{-1}$  (● Table 3) after the training period and



**Fig. 3** Relative changes (mean ± SD) in time to reach force level 1500 N in isometric action of the leg extensors and in early average IEMG (in 500 ms) of the VL + VM + RF in isometric action during the 8-week training period in the experimental and control group (\*  $p < 0.05$ , before vs. after 8-weeks of training within group, #  $p < 0.05$ , difference between the groups).



**Fig. 4** Maximal rate of force development (RFD) (mean ± SD) of the isometric action of the leg extensors before and after the 8-week training period in the experimental and control group (\*  $p < 0.05$ , before vs. after 8-weeks of training).

at this velocity the improvement ( $3 \pm 4\%$ ) in running economy approached the significance level ( $p = 0.07$ ) in E (Table 3). The lactate accumulation at the velocities of 12 and 14  $\text{km} \cdot \text{h}^{-1}$  decreased in E by  $12 \pm 20\%$  and  $11 \pm 15\%$ , respectively ( $p < 0.05$ ). No significant changes were recorded for C in any of these variables.

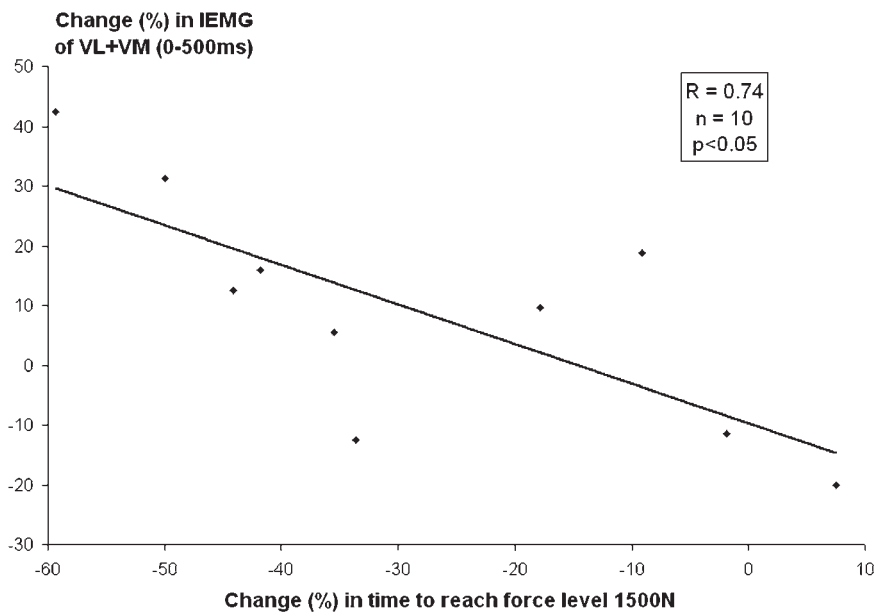
### Anthropometry

After the training period there was a significant increase in body weight by  $2 \pm 2\%$  ( $p < 0.01$ ) and increase in FFM approached significance ( $p = 0.056$ ) in group E (Table 1). The thickness of QF increased in E by  $3.9 \pm 4.7\%$  ( $p < 0.01$ ) and in C by  $1.9 \pm 2.0\%$  ( $p < 0.05$ ) (Table 1), but the changes did not differ significantly from each other. Thigh girths increased significantly ( $p < 0.05$ ) in

both groups (in E by  $1.6 \pm 1.9\%$  and in C by  $2.1 \pm 2.9\%$ ), but calf girth only in E by  $1.1 \pm 0.9\%$  ( $p < 0.01$ ) (Table 1).

### Serum hormone concentrations

No significant changes were observed in serum hormone concentrations measured for the males (Table 4). The correlation analysis of the pooled data showed that the mean of pre- and post-values of the total serum testosterone correlated significantly with the changes in  $V_{30}$  ( $r = 0.49$ ,  $p < 0.05$ ). Also the pre-value of the serum total testosterone/cortisol ratio correlated with the changes in CMJ ( $r = 0.54$ ,  $p < 0.05$ ) and with the changes in 5J ( $r = 0.53$ ,  $p < 0.05$ ) in the pooled data.



**Fig. 5** A correlation between the relative changes in early (0–500 ms) average IEMG of the VL + VM and change in time to reach force level 1500 N in isometric action of the leg extensors during the 8-week training period in the experimental group.

**Table 3** Oxygen consumption of different running velocities, maximal oxygen uptake and peak velocity in treadmill running in the experimental and the control groups before and after the 8-week training period

Variables	Experimental group (n = 9♂ + 4♀)			Control group (n = 9♂ + 3♀)			Group-by-training interaction
	Before	After	Change (%)	Before	After	Change (%)	
$\dot{V}O_2$ at 10 km/h	38.2 ± 2.8	38.7 ± 3.0	1.4 ± 6.6	38.1 ± 3.1	38.9 ± 3.0	2.6 ± 9.6	Ns.
$\dot{V}O_2$ at 12 km/h	45.0 ± 3.1	44.1 ± 3.3	-2.0 ± 4.1	45.1 ± 3.7	45.9 ± 3.9	2.2 ± 10.0	Ns.
$\dot{V}O_2$ at 13 km/h	48.1 ± 3.2	47.4 ± 3.3	-1.2 ± 4.7	47.6 ± 4.1	49.0 ± 3.4	3.5 ± 9.9	Ns.
$\dot{V}O_2$ at 14 km/h	52.1 ± 3.1	50.6 ± 3.6	-2.7 ± 4.3	51.0 ± 4.3	52.3 ± 3.9	2.7 ± 6.4	p < 0.05
$\dot{V}O_{2max}$	62.4 ± 5.4	62.8 ± 5.8	0.7 ± 5.5	61.8 ± 5.3	62.8 ± 5.6	1.8 ± 3.5	Ns.
$V_{END}$ , km/h	17.2 ± 1.0	17.4 ± 1.0	1.2 ± 4.7	17.1 ± 1.0	17.3 ± 1.4	1.2 ± 3.3	Ns.

Values are means ± SD. ♂ = male, ♀ = female,  $V_{END}$  = the peak velocity of the incremental treadmill test. Oxygen consumption values are expressed as  $ml \cdot kg^{-1} \cdot min^{-1}$

**Table 4** Serum concentrations of testosterone, free testosterone and cortisol of the males of the experimental and control groups before and after the 8-week training period

Variables	Experimental group (n = 9♂)		Control group (n = 9♂)	
	Before	After	Before	After
Testosterone ( $nmol \cdot l^{-1}$ )	20.1 ± 6.0	19.6 ± 5.3	14.9 ± 3.9	15.2 ± 6.6
Free testosterone ( $pmol \cdot l^{-1}$ )	14.2 ± 6.6	13.7 ± 6.3	12.8 ± 3.1	12.5 ± 4.6
Cortisol ( $\mu mol \cdot l^{-1}$ )	0.147 ± 0.117	0.106 ± 0.088	0.162 ± 0.145	0.132 ± 0.042

Values are means ± SD. ♂ = male

## Discussion

The present study showed that replacing about 20% of endurance training by explosive strength training for eight weeks improved anaerobic and selective neuromuscular performance characteristics in young distance runners without decreases in aerobic characteristics. The data further indicate that the gains in explosive strength and speed could be explained primarily by neural adaptations and to a lesser degree by muscle hypertrophy. Interestingly, the concurrent explosive type strength and endurance training had only a slight positive effect on running economy and no significant effect on endurance performance. Based on Noakes et al. [25] and Paavolainen et al. [27] the distance running performance is influenced not only by maximal oxygen uptake and running economy but also by neuromuscular

characteristics and muscle power factors.  $V_{MART}$  was used as a measure of muscle power factors, because during MART the athletes have to produce force/power in situations where glycolytic and/or oxidative energy production and/or muscle acidity are high and muscle contractility may be limited [27,29]. In the present study  $V_{MART}$  and several neuromuscular characteristics ( $V_{30}$ ,  $F_{ISOM}$ , 1RM, RFD) improved as a result of the concurrent explosive type strength and endurance training. This is in line with studies of Nummela et al. [26] and Paavolainen et al. [27] suggesting that the capability of the neuromuscular system to produce force rapidly and repeatedly is an important factor in the  $V_{MART}$ . However, in the present study the changes in neuromuscular parameters in our young subjects did not correlate with the changes in  $V_{MART}$ . All the submaximal velocities ( $V_{10}$ ,  $V_7$ ,  $V_5$ ,  $V_3$ ) at lactate levels of 3–10 mmol/l in MART increased in E,

which means that subjects could run at the same velocity with smaller anaerobic energy production [29]. This might be beneficial in endurance sports, because acidity, due to anaerobic metabolism, may limit the muscle contractility [29]. Also C improved  $V_7$  and  $V_3$  and this observation suggests that endurance training itself can improve “anaerobic running economy” at these velocities. Because only the concurrent explosive type strength and endurance training produced improvements in  $V_{10}$  and especially in  $V_{MART}$ , it seems that neuromuscular abilities ( $V_{30}$ ,  $F_{ISOM}$ , 1RM, RFD) are more essential at these higher velocities.

In the present study the improvements in the anaerobic and neuromuscular characteristics did not lead to better endurance performance ( $V_{END}$ ). This observation differs from the previous study of Paavolainen et al. [27], in which the adult athletes improved 5 km track running performance after the same kind of 9-week mixed training program as used in the present study. However, it is notable that in the present study the subjects were younger athletes and the volume of the explosive training was smaller. Previously also Spurrs et al. [32] found improvement in track running performance as a result of a 6-week plyometric training period in adult endurance runners.

It has been suggested that neuromuscular improvements related to explosive type strength training can be transferred not only into improved muscle power factors but also into improved running economy and consequently to better running performance [27]. It has been shown in many studies [19,22,27,32,33] that combined strength (explosive/heavy weight/plyometric) and endurance training improves running economy. In the present study the improvements in neuromuscular and muscle power characteristics did lead only to slight (ns.) improvements in running economy, even though there was a significant group-by-training interaction. However, because this interaction was partly a result of the negative trend of the running economy in C, the effect of concurrent explosive strength and endurance training on the true improvement in running economy in young athletes needs further investigation. In addition, it must be taken into account that the body mass of E increased during the training period and because unit of running economy is defined as  $ml \cdot kg^{-1} \cdot min^{-1}$ , it may induce an error because submaximal oxygen consumption during running does not increase in proportion to body mass [5].

The mechanism of improvement in running economy due to concurrent endurance and strength training in athletes could be explained by several factors. The increased maximal force of trained muscles might affect the recruitment of muscles so that athletes are able to use relatively more type I motor units leading to more economical endurance performance [12]. It has also been suggested that improved muscle stiffness due to combined explosive type strength and endurance training enhances running economy especially when strength training is carried out using stretch-shortening cycle type exercises [27,32]. Improved stiffness of the musculotendinous system may enhance the body's ability to store and utilize elastic energy and reduce the energy cost of the movement [35]. Because the volume of the plyometric training in the present study remained rather low (one session a week) and, therefore, no changes took place in the jump test performances (CMJ or 5J) to indicate improved explosive strength and ability to utilize elastic energy. Actually, this might be one reason why the running economy did not improve as much as one could have been expected in the present study. For example, in studies of Spurrs et al. [32] and Paavolainen et al. [27] endurance athletes improved their jumping abil-

ities and also running economy during the mixed training period. In those studies both the volume of plyometric training or total volume of the explosive training was greater than in the present study. On the contrary, Turner et al. [33] observed no changes in jumping variables (CMJ) or jumping efficiency), although running economy improved in the result of plyometric training (3 sessions a week) in regular trained distance runners. It is thus possible that one could improve running economy (although in the present study the improvement in running economy was minor) without improving vertical jumping test results, because e.g. the movement pattern of running is more forward directed than in jumping. However, great caution should be exercised with regard to the interpretation of the jumping tests (CMJ, 5J etc.), especially among endurance runners who traditionally do not include jumping exercises in their training programs.

In the present study the improvements in the maximal forces of the leg muscles were of the same magnitude as observed in previous studies on adult subjects.  $F_{ISOM}$  and 1 RM increased by 8% and 4% respectively and this is in line with studies of Paavolainen et al. [27], Spurrs et al. [32] and Millet et al. [22]. Improvements in those studies were 7% ( $F_{ISOM}$ ), 11–13% ( $F_{ISOM}$ ) and 5% (1RM), respectively. In addition, the improvement in maximal running speed ( $V_{30}$ ) in the present study was similar to the study of Paavolainen et al. [27]. Thus, this study suggests that postpubertal athletes (16–18 years) have similar training adaptations to mixed training in relation to force and velocity as adult endurance athletes. This agrees with the suggestion that in junior (17 years) weightlifters the effects of resistance training on the neuromuscular system are comparable to adaptations reported to take place among adult strength athletes [17].

In addition to improvements in maximal forces, the young distance runners improved their rapid force production of the leg extensors in isometric action. These changes in rapid force production were accompanied by the increase of IEMG (average for VL + VM + RF) during the early portion (0–500 ms) of the isometric action. The significant correlations observed in E between the individual changes in early forces and changes in early EMG-activities indicate a strong neural component of the adaptation. This finding is similar with previous studies in untrained men [16] and women [18] suggesting that explosive type strength training results in increases in the amount of neural input to the agonist muscles during isometric (and rapid dynamic) actions. This increase of neural input may come from increases in the firing frequency of motor units and brief interspike intervals or “doublets” in the EMG burst [34]. It has also been suggested, that although neural activation of the trained muscles during explosive strength training is high, the time of the muscle activation is so short that the training-induced muscle hypertrophy takes place to a smaller degree than during traditional heavy-resistance training [14,31]. In the present study significant (although minor in magnitude) hypertrophic adaptations took place as indicated by the increases in thigh muscle thickness and thigh circumference in E after the present concurrent explosive strength and endurance training. Because also the individual improvements in  $F_{ISOM}$  correlated with the increases in maximum EMG activity, it is suggested that in young athletes already rather a low volume of explosive type strength training may increase maximal force, and this improvement seems to be mainly associated with training-induced neural adaptations. The data indicated that some hypertrophic adaptations occurred during

the experimental period also in C, which might be related in part to natural maturation of young athletes.

The hormonal data of the present young postpubertal males suggests that the concurrent strength and endurance training program was not too strenuous, because there were no significant changes in the catabolic or anabolic hormonal environment during the training period. This might be explained by the fact that the experimental group did not increase the total training volume and thus the total training load was kept reasonable. The basal concentrations of the measured hormones were somewhat lower compared to adults (e.g. 1) suggesting that biological maturation was still occurring among our subjects [24]. However, great individual variation was observed in the basal concentrations of testosterone and cortisol and these differences in basal testosterone levels were associated with the individual changes in neuromuscular characteristics ( $V_{30}$ , 5J, CMJ) during the training period. This suggests that among young endurance athletes the trainability of neuromuscular characteristics was largely individual and associated with biological maturation. This should be taken account when designing the training programs for the young athletes.

According to the present study the training adaptations to concurrent explosive strength and endurance training in young athletes (age 16–18 years) are quite similar compared to adaptations in adult athletes. Only the endurance running performance and partly the running economy were not improved as one could expect. Naughton et al. [24] have suggested that the trainability of aerobic, anaerobic and neuromuscular characteristics in young athletes most likely depends on the initial fitness level of the athletes, their training background and the quality and duration of the intervention. The fact that in the present study the volume of the explosive strength training was rather low (19% of the total training hours) might have been the primary reason for the lack of additional improvement also for endurance performance compared to previous studies (e.g. 27) with adult athletes. The length of the training period should have been long enough (eight weeks), because it has been shown that already a 6-week training period is long enough to produce positive effects on running economy and endurance performance [32,33]. In summary, the improvements in neuromuscular and anaerobic characteristics in the present young endurance athletes were achieved without impairment in maximal oxygen uptake. This is in line with previous studies [19,22,27,32,33] showing no changes in  $\dot{V}O_{max}$ , although the volume of the endurance training was somewhat reduced. This is an encouraging observation in young endurance athletes and their coaches giving possibility to apply the results in their training programs. Although the endurance performance was not improved in treadmill running, it does not mean that young endurance athletes would not benefit from this kind of mixed training, since improved sprinting abilities ( $V_{30}$ ) and anaerobic performance capacity (improvements in MART) might give some advantage to their competitive performance, especially for the running events characterized by sprinting actions at the end of the race.

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