Explosive-strength training improves 5-km running time by improving running economy and muscle power

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Paavolainen, Leena, Keijo Häkkinen, Ismo Hämäläinen, Ari Nummela, and Heikki Rusko. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *J. Appl. Physiol.* 86(5): 1527–1533, 1999.—To investigate the effects of simultaneous explosive-strength and endurance training on physical performance characteristics, 10 experimental (E) and 8 control (C) endurance athletes trained for 9 wk. The total training volume was kept the same in both groups, but 32% of training in E and 3% in C was replaced by explosive-type strength training. A 5-km time trial (5K), running economy (RE), maximal 20-m speed (V_{20m}), and 5-jump (5J) tests were measured on a track. Maximal anaerobic (MART) and aerobic treadmill running tests were used to determine maximal velocity in the MART (V_{MART}) and maximal oxygen uptake ($\dot{V}O_{2max}$). The 5K time, RE, and V_{MART} improved ($P < 0.05$) in E, but no changes were observed in C. V_{20m} and 5J increased in E ($P < 0.01$) and decreased in C ($P < 0.05$). $\dot{V}O_{2max}$ increased in C ($P < 0.05$), but no changes were observed in E. In the pooled data, the changes in the 5K velocity during 9 wk of training correlated ($P < 0.05$) with the changes in RE [O_2 uptake ($r = -0.54$)] and V_{MART} ($r = 0.55$). In conclusion, the present simultaneous explosive-strength and endurance training improved the 5K time in well-trained endurance athletes without changes in their $\dot{V}O_{2max}$. This improvement was due to improved neuromuscular characteristics that were transferred into improved V_{MART} and running economy.

distance running; neuromuscular characteristics; maximal oxygen uptake; maximal anaerobic treadmill running; endurance athletes

ENDURANCE TRAINING ENHANCES the function of the cardiorespiratory system and the oxidative capacity and glycogen stores of the muscles (e.g., Refs. 1, 20). Heavy-resistance strength training results in neural and muscle hypertrophic adaptations that are known to be primarily responsible for improved strength performance (e.g., Refs. 13, 15). A specific type of strength training, explosive-strength training, may lead to specific neural adaptations, such as the increased rate of activation of the motor units, whereas muscle hypertrophy remains much smaller than during typical heavy-resistance strength training (13, 15, 39).

It has been suggested that simultaneous training for both strength and endurance may be associated with limited strength development during the later weeks of training, whereas the development of maximal O_2 uptake ($\dot{V}O_{2max}$) is not influenced as much (e.g., Refs. 10, 16, 18, 22). These observations are mainly based on experiments in which heavy-resistance strength training has predominated and the subjects have been previously untrained. However, proper strength training used simultaneously with endurance training may also result in some improvements in strength performance of endurance athletes (22, 35).

Many endurance-sport events require high aerobic power, and $\dot{V}O_{2max}$ is a good predictor of endurance performance in untrained subjects. However, some other factors, such as running economy (RE) or peak treadmill running performance, may be better predictors of endurance performance than $\dot{V}O_{2max}$ in a homogeneous group of well-trained endurance athletes (e.g., Refs. 4, 6, 30, 32). The endurance athletes must also be able to maintain a relatively high velocity over the course of a race. This emphasizes the role of neuromuscular characteristics related to voluntary and reflex neural activation, muscle force and elasticity, and running mechanics (13) as well as the role of anaerobic characteristics in elite endurance athletes. Bulbulian et al. (5) and Houmard et al. (21) have shown that anaerobic characteristics can differentiate well-trained endurance athletes according to their distance running performance. Heavy-resistance strength training has improved the endurance performance of previously untrained subjects (e.g., Refs. 17, 28, 29) or RE of female distance runners (24) without changes in $\dot{V}O_{2max}$ suggesting that neuromuscular characteristics may also be important for endurance performance. Consequently, Noakes (31) and Green and Patla (12) have suggested that $\dot{V}O_{2max}$ and endurance performance may be limited not only by central factors related to O_2 uptake ($\dot{V}O_2$) but also by so-called "muscle power" factors affected by an interaction of neuromuscular and anaerobic characteristics.

In the present study, muscle power is defined as an ability of the neuromuscular system to produce power during maximal exercise when glycolytic and/or oxidative energy production are high and muscle contractility may be limited. Peak velocity ($V_{\dot{V}O_{2max}}$) reached during the $\dot{V}O_{2max}$ treadmill running test has been shown to be a good indicator of endurance performance in middle- and long-distance running events (e.g., Refs. 4, 31, 32). Noakes (31) has suggested that $V_{\dot{V}O_{2max}}$ could also be used as a measure of the muscle power factor in endurance runners. However, in addition to the neuromuscular and anaerobic characteristics, the aerobic processes are also strongly involved in $V_{\dot{V}O_{2max}}$ (e.g., Ref.

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19). Recently, it has been suggested that peak velocity in the maximal anaerobic running test (V_{MART}), which is influenced both by the anaerobic power and capacity and by the neuromuscular characteristics without the influence of $\dot{V}O_{2max}$ could be used as a measure of muscle power (38).

The purpose of this study was to investigate the effects of simultaneous explosive-strength and endurance training on 5-km running performance, aerobic power, RE, selected neuromuscular characteristics, and muscle power in well-trained endurance athletes.

METHODS

Subjects. The experimental (E) group consisted of 12 and the control (C) group of 10 elite male cross-country runners (orienteers), and the groups were matched with regard to $\dot{V}O_{2max}$ and 5-km time trial. During the study period, two E and two C athletes were excluded because of injuries or illness. The physical characteristics of both groups before and after the experimental period are presented in Table 1. The percentage of body fat was estimated from the thickness of four skinfolds (triceps brachii, biceps brachii, subscapula, and suprailium) (11). The right calf and thigh girths were measured with a tape applied around the relaxed muscles. This study was approved by the Ethics Committee of the University of Jyväskylä, Jyväskylä, Finland.

Training. The experimental training period lasted for 9 wk and was carried out after the competition season. The total training volume was the same in both E and C groups (8.4 ± 1.7 h and 9 ± 2 times/wk and 9.2 ± 1.9 h and 8 ± 2 times/wk, respectively), but 32% of training hours in the E group and 3% in the C group were replaced by sport-specific explosive-strength training. The rest of the training in both groups was endurance training and circuit training (Fig. 1). Explosive-strength training sessions lasted for 15–90 min and consisted of various sprints (5–10)·(20–100 m) and jumping exercises [alternative jumps, bilateral countermovement, drop and hurdle jumps, and 1-legged, 5-jump (5J) tests] without additional weight or with the barbell on the shoulders and leg-press and knee extensor-flexor exercises with low loads but high or maximal movement velocities (30–200 contractions/training session and 5–20 repetitions/set). The load of the exercises ranged between 0 and 40% of the one-repetition maximum. Endurance training of both groups consisted of

Table 1. *Training background of the experimental and control groups and their physical characteristics before and after 9 wk of training*

Variable	Experimental Group ($n = 10$) Before	Experimental Group ($n = 10$) After	Control Group ($n = 8$) Before	Control Group ($n = 8$) After
Age, yr	23 ± 3		24 ± 5	
Training background, yr	8 ± 3		9 ± 4	
Training, h/yr	532 ± 27		562 ± 31	
Sprint and explosive strength, times/wk	0–1		0–1	
Height, cm	179.3 ± 5.3	179.3 ± 5.3	181.5 ± 6.2	181.5 ± 6.2
Body weight, kg	71.9 ± 4.9	72.3 ± 4.4	70.2 ± 4.2	69.4 ± 3.9
Fat, %	9.5 ± 2.1	9.2 ± 2.7	8.9 ± 1.8	8.6 ± 1.5
Calf girth, cm	35.7 ± 1.4	35.9 ± 1.7	35.2 ± 1.8	35.1 ± 1.9
Thigh girth, cm	51.6 ± 2.1	51.7 ± 2.2	50.8 ± 1.9	50.7 ± 2.0

Values are means ± SD. n, No. of subjects.

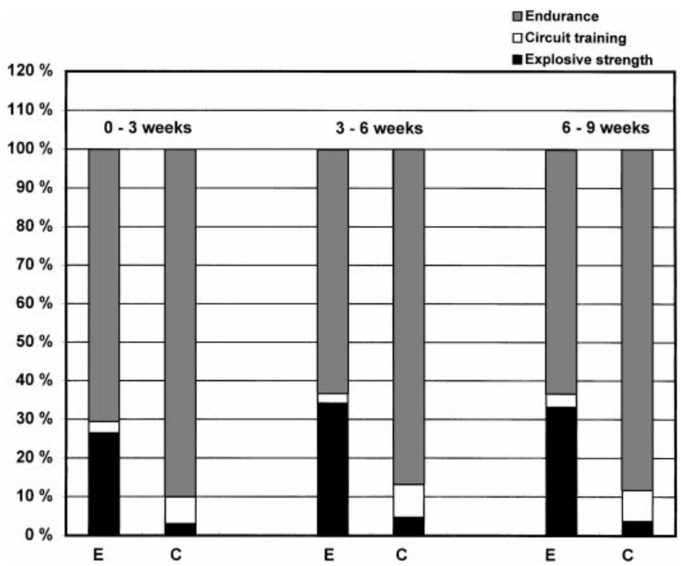

Fig. 1. Relative volumes of different training modes in experimental (E) and control (C) groups during course of 9-wk simultaneous explosive-type strength and endurance training.

cross-country or road running for 0.5–2.0 h at the intensity below (84%) or above (16%) the individual lactate threshold (LT). Circuit training was similar in both groups; the C group trained more often than did the E group, and training consisted of specific abdominal and leg exercises with dozens of repetitions at slow movement velocity and without any external load.

Measurements. The E and C groups were examined before training and after 3, 6, and 9 wk of training, except for the 5-km time trial (5K), which was only performed before and after 6 and 9 wk of training. The schedule of two measurement days is seen in Table 2. On the first day, after the anthropometric measurements and a warm-up, the maximal isometric force of the leg extensor muscles was measured on an electromechanical dynamometer (15). Three to five maximal isometric contractions were performed at the knee and hip angles of 110°. The force in each contraction was recorded by a microcomputer (Toshiba T3200 SX) by using an AT Codas analog-to-digital converter card (Dataq Instruments).

$\dot{V}O_{2max}$ and LT were determined during the maximal aerobic power test on a treadmill. The initial velocity and inclination were 2.22 m/s and 1°, respectively. The velocity was increased by 0.28 m/s after every 3-min stage until the velocity of 4.75 m/s was reached, except for two velocity increases of 0.56 m/s in the middle of the test. After 4.75 m/s was reached, the velocity was kept constant but the inclination was increased by 1° every minute until exhaustion. Fingertip blood samples were taken after each velocity to determine blood lactate concentrations by an enzymatic-electrode method (EBIO 6666, Eppendorf-Netheler-Hinz). Ventilation and $\dot{V}O_2$ for every 30-s period were measured by using a portable telemetric O_2 analyzer (Cosmed K2) (7). The LT as $\dot{V}O_2$ (ml·kg^{-1}·min^{-1}) was determined at the point at which blood lactate concentration distinctly increased from its baseline of 1–2 mmol/l (2, 23) and was verified by using respiratory data (2, 40). $\dot{V}O_{2max}$ was taken as the highest mean of two consecutive 30-s $\dot{V}O_2$ measurements (ml·kg^{-1}·min^{-1}). Because the inclination of the treadmill was increased and the velocity was kept constant during the last stages of the test, peak treadmill running performance was calculated not as the peak velocity ($V_{\dot{V}O_{2max}}$) but as the O_2 demand of running during the last minute before exhaustion

Table 2. *Chronological presentation of the measurements performed on days 1 and 2*

Day 1 (Treadmill Measurements)					*Day 2* (Track Measurements)				
Dynamometer test Maximal isometric force	Recovery (10 min)	Maximal aerobic power test $\dot{V}O_{2\,max}$ LT	Recovery (20 min)	MART V_{MART}	20-m and 5J test $V_{20\,m}$ and CT Distance, m	Recovery (10 min)	Submaximal running $RE_{track\,1}$ $RE_{track\,2}$	Recovery (10 min)	5K V_{5K} CVLs CT, SR, SL, F_z, F_y

$\dot{V}O_{2\,max}$, maximal O_2 uptake; LT, lactate threshold; MART, maximal anaerobic running test; V_{MART}, maximal velocity of the MART; 5J, 5 forward jumps; $V_{20\,m}$, maximal 20-m velocity; CT, contact time; RE, running economy; 5K, 5-km time trial; V_{5K}, average velocity of 5K; CVL, constant-velocity lap (200 m); SR, stride rate; SL, stride length; F_z and F_y, vertical and horizontal ground reaction force, respectively.

($\dot{V}O_{2\,max,demand}$) by using the formula of the American College of Sports Medicine (1991)

$$\dot{V}O_2\ (ml \cdot kg^{-1} \cdot min^{-1}) = 0.2 \cdot v\ (m/min) + 0.9 \cdot grade\ (frac) \cdot v\ (m/min) + 3.5$$

where v is the speed of the treadmill, grade is the slope of the treadmill expressed as the tangent of the treadmill angle with the horizontal, and frac is fraction.

After 20 min of recovery the subjects performed a MART (37), which consisted of a series of 20-s runs on a treadmill with a 100-s recovery between the runs. A 5-s acceleration phase was not included in the running time. The first run was performed at a velocity of 3.71 m/s and a grade of 4°. Thereafter, the velocity of the treadmill was increased by 0.35 m/s for each consecutive run until exhaustion. Exhaustion in the MART was determined as the time when the subject could no longer run at the speed of the treadmill. V_{MART} was determined from the velocity of the last completed 20-s run and from the exhaustion time of the following faster run (37).

On the second day, the subjects performed four tests on a 200-m indoor track: a maximal 20-m speed ($V_{20\,m}$) test, a 5J, a submaximal RE test, and a 5K (Table 2). After a 20-min warm-up the subjects ran three times the maximal 20-m run with a running start of 30 m and performed the 5J test three to five times. The 20-m running times were measured by two photocell gates (Newtest, Oulu, Finland) connected to an electronic timer, and the $V_{20\,m}$ was recorded. The 5J was started from a standing position, and the subjects tried to cover the longest distance by performing a series of five forward jumps with alternative left- and right-leg contacts. The distance of the 5J was measured with a tape.

Ten minutes after the $V_{20\,m}$ and 5J tests, the subjects performed the RE test (2 · 5 min). The velocity of the runs was guided by a lamp speed-control system ("light rabbit," Protom, Naakka, Finland). $\dot{V}O_2$ during the runs was measured by using the portable telemetric O_2 analyzer (Cosmed K2) and track RE was calculated as a steady-state $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$) during the last minute of running at the 3.67 and 4.17 m/s velocities.

Ten minutes after the RE test, the subjects performed the 5K on the 200-m indoor track. The mean velocity of the 5K (V_{5K}) was calculated. At the beginning of the 5K and after running 2.5 and 4 km, all subjects ran one 200-m constant-velocity lap (CVL) at the 4.55 m/s velocity through the photocell gates. The velocity of the CVLs was guided by the lamp speed-control system. The CVLs were run over a special 9.4-m-long force-platform system, which consisted of five two- and three three-dimensional force plates (0.9/1.0 m, TR Testi, natural frequency in the vertical direction 170 Hz) and one Kistler three-dimensional force platform (0.9/0.9 m, 400 Hz, Honeycomb, Kistler, Switzerland) connected in series and covered with a tartan mat. Each force plate registered both vertical (F_z) and horizontal (F_y) components of the ground reaction force. F_z, F_y, and contact times (CT) were recorded by a microcomputer (Toshiba T3200 SX) by using an AT Codas analog-to-digital converter card (Dataq Instruments) with a sampling frequency of 500 Hz. Stride rates (SR) were calculated by using CTs and flight times (FT) [1/(CT + FT)] and stride lengths by using velocity and SRs (V/SR). Each run included four to six contacts on the force-platform system. The horizontal force-time curve was used to separate the CT and F_z and F_y force components into the braking and the propulsion phases. The integrals of both force-time curves were calculated and divided by the respective time period to obtain the average force for the whole contact phase and for the braking and propulsion phases separately.

Statistical methods. Means and SDs were calculated by standard methods, and Pearson correlation coefficients were used to evaluate the relationships among the variables. The significance of changes between the test values and differences within the E and C groups were tested by multiple analysis of variance for repeated measures (MANOVA). If a significant F-value was observed, Student's t-test was used to identify differences within groups. Because of slight initial group differences, analysis of covariance by using the pretest values as the covariate was employed to determine significant differences between the posttest adjusted means in the E group and those in the C group.

RESULTS

The 5K time did not differ significantly between the groups before the experiment, but, according to analysis of covariance, E and C group 5K times were different

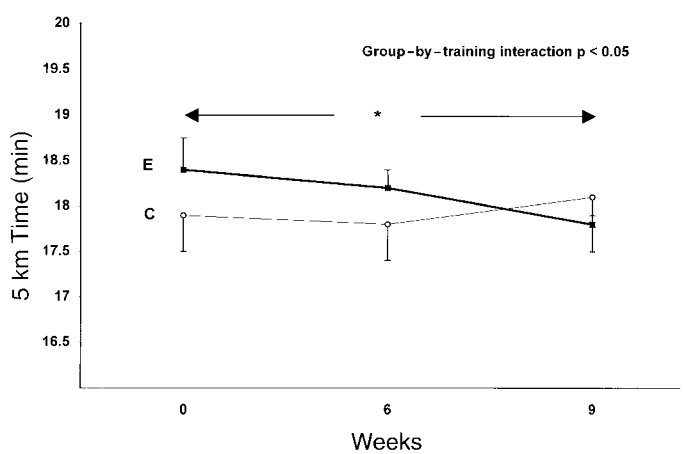

Fig. 2. Average (±SD) 5-km running time in E and C groups during course of 9-wk simultaneous explosive-type strength and endurance training. *$P < 0.05$.

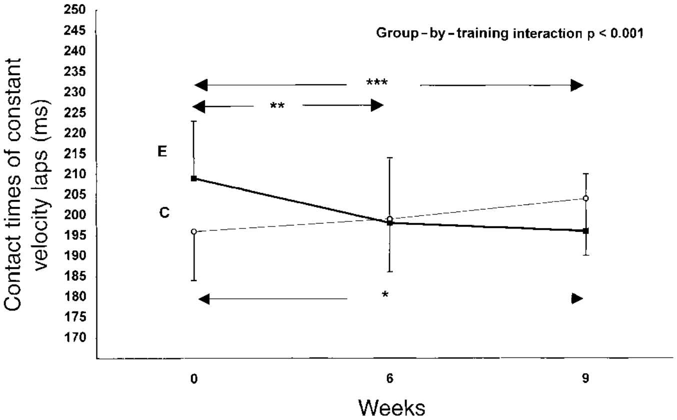

Fig. 3. Average (±SD) ground contact times of constant-velocity laps in E and C groups during course of 9-wk simultaneous explosive-type strength and endurance training. *$P < 0.05$. **$P < 0.01$. ***$P < 0.001$.

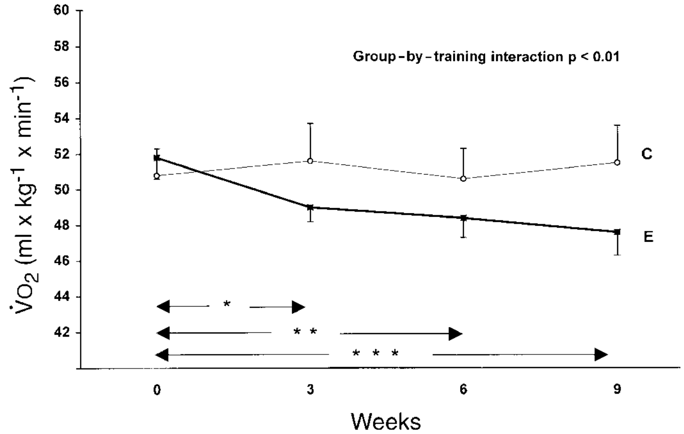

Fig. 4. Average (±SD) steady-state O_2 uptake during last minute of running at submaximal velocity of 4.17 m/s velocity in E and C groups during course of 9-wk simultaneous explosive-type strength and endurance training. *$P < 0.05$. **$P < 0.01$. ***$P < 0.001$.

($P < 0.05$) after training. Significant group-by-training interaction was found in the 5K time after 9 wk of training. It decreased ($P < 0.05$) during the training period in E group, whereas no changes were observed in the C group (Fig. 2). During the CVLs of the 5K, the CTs decreased in the E group ($P < 0.001$) and increased in the C group ($P < 0.05$) during the training period (Fig. 3). Significant differences ($P < 0.001$) were observed in adjusted mean CTs of CVLs between the E and C group after training. No significant differences or changes during the training period were observed in either the E or C group in the ground reaction forces, SRs, or stride lengths of CVLs during the 5K.

RE, V_{MART}, and $\dot{V}O_{2\,max,demand}$ did not differ between the groups before the experiment, but after 9 wk of training, adjusted RE ($P < 0.001$) and V_{MART} ($P < 0.01$) in the E and C groups were different. Significant group-by-training interaction was found in RE and V_{MART} after the training period, and RE, V_{MART}, as well as $\dot{V}O_{2\,max,demand}$, improved ($P < 0.05$) in the E group, whereas no changes were observed in the C group (Table 3 and Figs. 4 and 5). Significant group-by-training interaction ($P < 0.05$) was also found in $\dot{V}O_{2\,max}$ after 9 wk of training, with an increase in the C group ($P < 0.01$) and no change in the E group (Table 3). No significant changes or differences were found in either the E or C group in the LT during the training period (Table 3).

Maximal isometric force of the leg extensor muscles, $V_{20\,m}$, and 5J did not differ significantly between the E and C groups before the experiment, but analysis of covariance showed significant ($P < 0.01$) differences after 9 wk of training (Table 4). Maximal isometric force tended to increase in the E group and to decrease in the C group during the training period. The changes were not statistically significant, but a significant group-by-training interaction was found in maximal isometric force (Table 4). $V_{20\,m}$ and 5J increased in the E group by 3.6–4.7% ($P < 0.01$) and decreased in the C group by 1.7–2.4% ($P < 0.05$) after 9 wk of training, and significant group-by-training interactions were observed as well (Table 4).

The correlation analysis of pooled data showed that the improvement in the V_{5K} correlated significantly ($P < 0.05$) with the improvement in $\dot{V}O_{2\,max,demand}$ (r = 0.63), RE (expressed as $\dot{V}O_2$, $ml \cdot kg^{-1} \cdot min^{-1}$) ($r$ = −0.54), and V_{MART} (r = 0.55). The correlation coefficient between the changes in $\dot{V}O_{2\,max}$ and in the V_{5K} was negative (r = −0.52, $P < 0.05$). The improvements in RE and V_{MART} correlated with each other (r = −0.65, $P < 0.01$) and were associated ($P < 0.05$) with increases in $\dot{V}O_{2\,max,demand}$ (r = −0.62 and 0.64), 5J (r = −0.63 and 0.68), and $V_{20\,m}$ (r = −0.49 and 0.69), respectively.

DISCUSSION

It has been shown (36) that adult endurance athletes who continue their endurance training for several years seem to reach a more or less apparent ceiling of $\dot{V}O_{2\,max}$ and endurance performance. Some previous training studies (17, 28, 29) have found that strength

Table 3. $\dot{V}O_{2\,max,demand}$, $\dot{V}O_{2\,max}$, and LT in the experimental and control groups in the maximal aerobic power test on the treadmill before and after 3, 6, and 9 wk of training

	Experimental Group ($n = 10$)				Control Group ($n = 8$)				
Variable	Before	After 3 wk	After 6 wk	After 9 wk	Before	After 3 wk	After 6 wk	After 9 wk	Interaction
$\dot{V}O_{2\,max,demand}$, $ml \cdot kg^{-1} \cdot min^{-1}$	67.7 ± 2.8	68.4 ± 3.1	68.9 ± 2.8	70.2 ± 2.5*	68.3 ± 3.1	68.4 ± 3.6	68.9 ± 2.8	69.2 ± 3.1	NS
$\dot{V}O_{2\,max}$, $ml \cdot kg^{-1} \cdot min^{-1}$	63.7 ± 2.7	63.9 ± 1.9	63.4 ± 3.7	62.9 ± 3.2	65.1 ± 4.1	65.3 ± 5.9	67.1 ± 4.1	68.3 ± 3.4†	$P < 0.05$
LT, $ml \cdot kg^{-1} \cdot min^{-1}$	47.3 ± 3.3	47.9 ± 2.5	47.8 ± 3.4	48.1 ± 3.5	48.9 ± 4.5	48.9 ± 3.3	49.1 ± 2.1	49.3 ± 2.8	NS

Values are means ± SD. $\dot{V}O_{2\,max,demand}$, peak uphill running performance; NS, not significant. *Significantly different from before, $P < 0.05$. †Significantly different from before, $P < 0.01$.

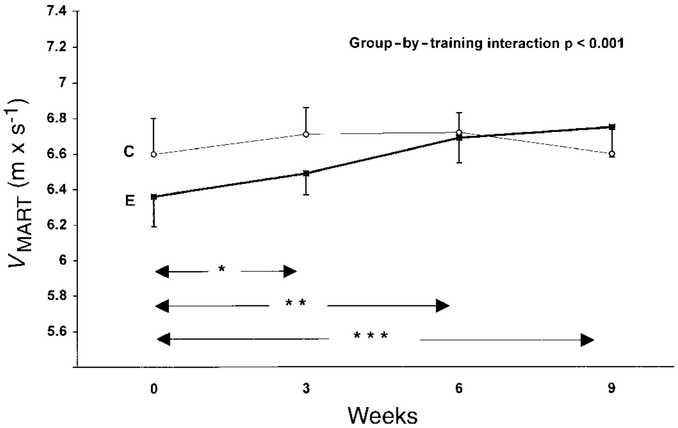

Fig. 5. Average (±SD) peak velocity in maximal anaerobic running test (MART) in E and C groups during course of 9-wk simultaneous explosive-type strength and endurance training. $*P < 0.05$. $**P < 0.01$. $***P < 0.001$.

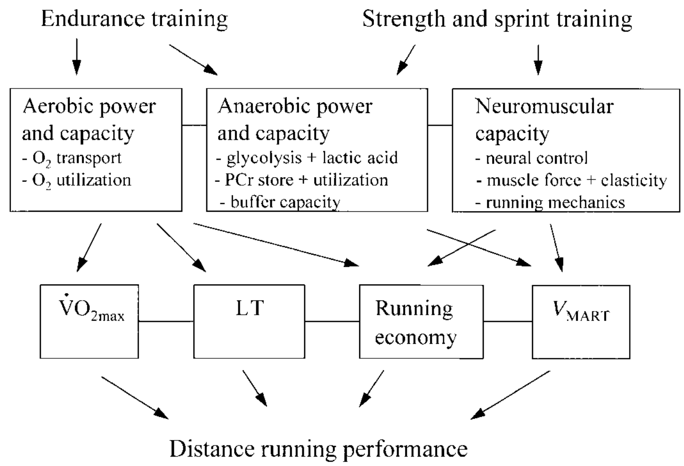

Fig. 6. Hypothetical model of determinants of distance running performance in well-trained endurance athletes as influenced by endurance and strength training. PCr, phosphocreatine; $\dot{V}O_{2\,max}$, maximal O_2 uptake; LT, lactate threshold; V_{MART}, peak velocity in MART.

training may lead to improved endurance performance in previously untrained subjects. The present study showed that simultaneous sport-specific explosive-strength and endurance training may also improve 5-km running performance (and peak treadmill running performance, i.e., $\dot{V}O_{2\,max,demand}$) of well-trained male endurance athletes. The mechanism of this improvement is suggested to be related to an explosive-strength-training effect: neuromuscular characteristics measured by $V_{20\,m}$, 5J, and CTs of CVLs were improved and transferred into improved muscle power (V_{MART}) and RE.

The present 9-wk explosive-type strength training resulted in considerable improvements in selected neuromuscular characteristics, although a large volume of endurance training was performed concomitantly. This was demonstrated by the significant improvements in $V_{20\,m}$ and 5J and by the shortening of the CTs during the CVLs of the 5K, whereas no changes were observed in the ground reaction forces or maximal force of the trained muscles. These results support our previous findings (35) that in well-trained endurance athletes training-induced improvements in neuromuscular characteristics may not be fully inhibited by simultaneous explosive-strength and endurance training.

It has been suggested (3, 26) that the nervous system plays an important role in regulating muscle stiffness and utilization of muscle elasticity during stretch-shortening cycle exercises, in which high contraction velocities are used. The present increases in neuromuscular performance characteristics might primarily be due to neural adaptations, although no electromyographic measurements in the muscles were done to support this suggestion. Although the loads used in the present explosive-strength training were low, the muscles are known to be highly activated because of the maximal movement velocity utilized (13). It has been shown that this type of explosive-strength training results in increases in the amount of neural input to the muscles observable during rapid dynamic and isometric actions (e.g., Refs. 14, 15), suggesting that the increase in net excitation of motoneurons could result from increased excitatory input, reduced inhibitory input, or both (39). It is likely that training-induced alterations in neural control during stretch-shortening cycle exercises such as running and jumping may take place in both voluntary activation and inhibitory and/or facilitatory reflexes (13, 25, 26, 39). Although neural activation of the trained muscles during explosive-type strength training is very high, the time of this activation during each single muscle action is usually so short that training-induced muscular hypertrophy and maximal strength development take place to a drastically smaller degree than during typical heavy-resistance training (13). Consequently, it has been suggested (35) that, during relatively short training periods of some weeks, the improvements in sprinting and/or explosive-force-production capacity, especially in endurance athletes, might primarily come from neural adaptations without observable muscle hypertrophy (see also Refs.

Table 4. *F, $V_{20\,m}$, and 5J in the experimental and control groups before and after 3, 6, and 9 wk of training*

	Experimental Group ($n = 10$)				Control Group ($n = 8$)				
Variable	Before	After 3 wk	After 6 wk	After 9 wk	Before	After 3 wk	After 6 wk	After 9 wk	Interaction
F, N	4,094 ± 891	4,123 ± 913	4,226 ± 987	4,385 ± 1,132§	3,899 ± 635	3,712 ± 362	3,651 ± 498	3,396 ± 648	$P < 0.01$
$V_{20\,m}$, m/s	7.96 ± 0.57	8.05 ± 0.53	8.11 ± 0.51	8.23 ± 0.54†·§	8.28 ± 0.35	8.21 ± 0.38	8.14 ± 0.21*	8.08 ± 0.31*	$P < 0.001$
5J, m	12.47 ± 0.90	12.60 ± 0.85	12.86 ± 0.95†	13.04 ± 0.83‡·§	13.17 ± 0.46	13.08 ± 0.59	13.10 ± 0.47	12.95 ± 0.50*	$P < 0.001$

Values are means ± SD. F, maximal isometric strength. *Significantly different from before, $P < 0.05$. †Significantly different from before, $P < 0.01$. ‡Significantly different from before, $P < 0.001$. §Significantly different from control group, $P < 0.01$.

17, 18). The finding that no changes took place in the circumferences of the calf and thigh muscles in our endurance athletes during the present training period supports this suggestion.

The rationale for this study was based on the hypothesis (see Fig. 6) that endurance performance and peak treadmill running performance are influenced not only by aerobic power and RE but also by the so-called muscle power factor, which is related to neuromuscular and anaerobic characteristics (e.g., Refs. 12, 31). This hypothesis is supported by the present findings that the correlation between the improvements in V_{5K} and in $\dot{V}O_{2\,max,demand}$ were associated with the changes in both RE and V_{MART}. An interesting finding that supports the muscle power factor was that, although the improvements in the neuromuscular characteristics ($V_{20\,m}$, 5J, CTs of CVLs) did not correlate directly with the changes in 5-km running performance, they correlated with V_{MART}, which was associated with improved V_{5K}. During both the MART and 5K, the athletes had to use their neuromuscular characteristics when $\dot{V}O_2$ and blood lactate concentration were considerably increased over resting values. Previous studies have shown that during fatigued conditions an increased H^+ concentration, which is related to the increased blood lactate concentration during the present 5K running, impairs the contractile propertiers of the muscles (e.g., Ref. 27). Moreover, during middle-distance running and uphill cross-country skiing, for example, energy expenditure may exceed maximal aerobic power and the athletes must be able to maintain a relatively high velocity over the course of a race although their muscle and blood lactate concentrations are high (9, 33; see also Ref. 38). This further emphasizes the importance of the muscle power factor (the ability of the neuromuscular system to produce power during maximal exercise when glycolytic and/or oxidative energy production are high and muscle contractility may be limited) in endurance sports (38).

The improvements in 5-km running performance by the present E group of athletes took place without changes in their $\dot{V}O_{2\,max}$ or LT. Interestingly, even a negative correlation was observed between the individual changes in $\dot{V}O_{2\,max}$ and the changes in 5K velocity. The present C group showed increased $\dot{V}O_{2\,max}$ but did not demonstrate changes in 5-km running performance. Furthermore, V_{MART} did not correlate with $\dot{V}O_{2\,max}$. All these results support the hypothesis of Noakes (31) and some other researchers (e.g., Ref. 12) that endurance performance may be limited not only by central factors related to $\dot{V}O_{2\,max}$ but also by the muscle power factor.

The improved neuromuscular characteristics of the present E athletes were related to both V_{MART} and RE. Improvements in $V_{20\,m}$, 5J, and CTs of the CVLs correlated with the improvement in V_{MART} during the training period. These results support the observation by Nummela et al. (34) that training utilizing various jumping and sprinting exercises with high contraction velocities and reaction forces results in increases in stretch-shortening cycle exercises such as sprint running and also allows improvements in V_{MART}. Moreover, these results are in line with previous observations that V_{MART} is influenced by the interaction of neuromuscular and anaerobic characteristics and that V_{MART} can be used as a measure of muscle power (37, 38).

Another possible mechanism for the improvement in the 5-km running performance seemed to be related to RE. It has been reported (24) that heavy-resistance strength training improved RE of female distance runners. The importance of the neuromuscular characteristics in determining RE and thereby running performance has recently been pointed out also by Dalleau et al. (8). They showed that the energy cost of running is significantly related to the stiffness of the propulsive leg, which is also demonstrated by the present decrease in the CTs of CVLs and increase in $V_{20\,m}$ and 5J in the E group. It has been suggested (9) that the 5% decrease in the energy cost of running explains an improvement in the distance running performance time of ~3.8%. This is in line with the results of the present study, in which RE and 5K time of the E group improved by 8.1 and 3.1%, respectively, and no changes in $\dot{V}O_{2\,max}$ were observed. Furthermore, the present correlations between the improvements in the neuromuscular characteristics and RE were statistically significant. All these findings, together with the relationship between the improvement in V_{5K} and RE, suggest that explosive-strength training had a positive influence on RE and running performance because of the improved neuromuscular characteristics. However, RE at race pace is different from that at submaximal running velocity. The significant correlation between RE and V_{MART} suggests that muscle power may influence RE both at submaximal velocities and most probably at race pace.

In conclusion, simultaneous explosive-strength training, including sprinting and endurance training, produced a significant improvement in the 5-km running performance by well-trained endurance athletes without changes in $\dot{V}O_{2\,max}$ or other aerobic power variables. This improvement is suggested to be due to improved neuromuscular characteristics that were transferred into improved muscle power and RE.

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