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ORIGINAL ARTICLE

Neuromuscular adaptations during combined strength and endurance training in endurance runners: maximal versus explosive strength training or a mix of both

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Abstract This study compared the effects of mixed maximal strength and explosive strength training with maximal strength training and explosive strength training combined with endurance training over an 8-week training intervention. Male subjects (age 21–45 years) were divided into three strength training groups, maximal (MAX, $n = 11$), explosive (EXP, 10) and mixed maximal and explosive (MIX, 9), and a circuit training control group, (CON, 7). Strength training one to two times a week was performed concurrently with endurance training three to four times a week. Significant increases in maximal dynamic strength (1RM), countermovement jump (CMJ), maximal muscle activation during 1RM in MAX and during CMJ in EXP, peak running speed (S_{peak}) and running speed at respiratory compensation threshold ($\text{RCT}_{\text{speed}}$) were observed in MAX, EXP and MIX. Maximal isometric strength and muscle activation, rate of force development (RFD), maximal oxygen uptake $\left(\dot{V}\text{O}_{2\,\text{max}}\right)$ and running economy (RE) at 10 and 12 km hr^{-1} did not change significantly. No significant changes were observed in CON in maximal isometric strength, RFD, CMJ or muscle activation, and a significant decrease in 1RM was observed in the final 4 weeks of training. RE in CON did not change significantly, but significant increases were observed in S_{peak}, $\text{RCT}_{\text{speed}}$ and $\left(\dot{V}\text{O}_{2\,\text{max}}\right)$. Low volume MAX, EXP and MIX strength training combined with higher volume endurance training over an 8-week intervention produced significant gains in strength, power and endurance performance measures of S_{peak} and $\text{RCT}_{\text{speed}}$, but no significant changes were observed between groups.

Keywords Concurrent training · Neuromuscular performance · Endurance performance · Running economy · Strength

Introduction

In recent years, the importance of neuromuscular performance in endurance sports has been examined by a number of researchers who have come to the general conclusion that strength training improves neuromuscular performance, while consequently improving sport-specific economy in endurance disciplines like running (Paavolainen et al. 1999; Taipale et al. 2010; Støren et al. 2008) and cross-country skiing (Paavolainen et al. 1991; Mikkola et al. 2007; Hoff et al. 2002). Improved neuromuscular performance includes, e.g., increases in voluntary muscle activation, which leads to increases in strength and power, associated with increased speed and decreased oxygen consumption at submaximal speeds (improved economy). Strength training, performed concurrently with endurance training has been reported to be beneficial to the neuromuscular characteristics of trained and untrained men and women of all ages (e.g., Hoff et al. 2002; Häkkinen et al. 2003; Mikkola et al. 2007; Paavolainen et al. 1991, 1999; Sillanpää et al. 2008; Støren et al. 2008; Taipale et al. 2010); however, an "interference effect" has also been reported when strength and endurance exercises are performed concurrently (Hickson 1980). The cause of the

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"interference effect" appears to be related to the divergent responses and adaptations to strength and endurance training, and is associated with high volume or intensity, long duration and mode of training (Wilson et al. 2011).

Within strength training, it is important to remember that there is a specificity effect of the training mode and its adaptations in the neuromuscular system. For example, maximal strength training with high loads (such as 70–90 % 1RM) and low repetitions per set generally result in neural adaptations followed by muscle hypertrophy over prolonged training periods. In contrast, explosive resistance training with low to medium loads (such as 30–60 % 1RM) but high action velocity movements improves the neuromuscular characteristics, especially rapid activation of the muscles due to increased motor unit recruitment. Both maximal and explosive strength training performed concurrently with endurance training have been shown to be more effective in improving strength, power and muscular activation in recreational endurance runners than concurrent circuit and endurance training (Mikkola et al. 2011; Taipale et al. 2010). A mix of maximal and explosive strength training in a single session and performed concurrently with endurance training may therefore be hypothesized to have an additive effect over maximal or explosive strength training performed concurrently with endurance training in recreational endurance runners.

It is commonly known that mode, intensity (Tremblay et al. 2005) and duration of training (Tremblay et al. 2005) also influence serum hormonal concentrations and that hormones play a significant role in adaptations to strength and endurance training. The typical acute serum hormonal response to a strength training session in men includes, e.g., an increase in serum testosterone (TESTO), while prolonged endurance exercise sessions cause significant increases in serum levels of cortisol (CORT) and/or a decrease in serum levels of TESTO. Acute changes in serum hormonal concentrations may lead to chronic changes in basal serum hormonal concentrations. In endurance trained men, Consitt et al. (2002) reported a decrease, or no change, in basal concentrations of hormones, while Hackney et al. (2003) reported decreased TESTO and increased CORT. Other hormones may also be affected by training and/or related stress. For example, decreased thyroid-stimulating hormone (TSH) has been linked to psychological stress (i.e., Nadolnik 2011) as well as physical stress (Pakarinen et al. 1991). Other research has suggested that prolonged strength training does not affect TSH levels (Pakarinen et al. 1988). Dehydroepiandrosterone sulfate (DHEAS) has also been shown to decrease with exercise stress (possibly as a result of oxidative stress) and aging (Aldred et al. 2009).

Based on our previous knowledge of the benefits of adding strength training to endurance training to improve neuromuscular performance and sport-specific economy, the purpose of the present study was to compare the effects of adding three different low volume modes of strength training performed concurrently with a higher volume of endurance training relative to strength training. Neuromuscular, cardiorespiratory and hormonal adaptations to training were examined in male recreational endurance runners over an 8-week strength training intervention. The strength training modes studied included mixed maximal and explosive strength training, maximal strength training and explosive strength training, while endurance training was similar across groups.

Methods

Subjects

Thirty-seven male recreational endurance runners (age 21–45 years) were recruited as part of a marathon training school and completed the study. The study design, including information on the possible risks and benefits of participation, were thoroughly explained prior to subjects signing an informed consent document. Ethical approval was granted by the university ethical committee and the study was conducted according to the most recent Declaration of Helsinki.

Subjects were divided into groups matched for age, anthropometrics, training experience, strength and endurance characteristics such as maximal oxygen uptake $\left(\dot{V}\mathrm{O}_{2\,\max}\right)$, peak running speed ($S_{\mathrm{peak}}$), running speed at lactate threshold (S_{LT}) and running speed at respiratory compensation threshold (S_{RCT}) following baseline testing, which was performed approximately 6 weeks prior to the strength training intervention. During the actual strength training intervention, groups included a maximal strength training group (MAX, $n = 11$, age: 35.5 ± 6.1 years, height: 178.6 ± 5.5 cm (mean ± SD)), an explosive strength training group (EXP, $n = 10$, 36.5 ± 6.5 years, 180.5 ± 6.4 cm) a mixed maximal and explosive strength training group (MIX, $n = 9$, 31.3 ± 8.9 years, 178.1 ± 5.3 cm) and a circuit training control group which used only their own body weight as a load (CON, $n = 7$, 33.7 ± 8.8 years, 180.0 ± 4.8 cm). There were no significant differences between groups at baseline. Subjects were not using medications and had no injuries that would affect physical performance.

Study design and training

This study is part of a large experimental design involving prolonged and periodized concurrent strength and endurance training. Some of the results obtained with the present subjects have been previously reported (Mikkola et al. 2011; Taipale et al. 2010). The unique purpose of this study was to compare mixed maximal and explosive strength training combined with endurance training to maximal strength training, explosive strength training and circuit training combined with endurance training in men. While data from the preparatory strength training period are not reported in this manuscript, it should be noted that the subjects performed 6 weeks of preparatory training (prior to this 8-week intervention) in which submaximal loads of 50 % progressing up to 70 % 1RM were used. The purpose of the 6-week preparatory strength training period was for subjects to learn proper lifting technique prior to the intervention. As subjects were previously untrained in terms of strength, it was also important to include this period in their training to avoid injury while also reducing the effect of learning on strength gains that may have otherwise occurred during the intervention period. Exercises used for the lower extremities during the 6-week preparatory period were the same as those used during the 8-week strength training intervention.

The present 8-week strength training program was focused on the leg extensors as they are a major muscle group at work in human locomotion and running and thus an important muscle group to study. The 8-week intervention period was used, because 8 weeks of strength training after a 6-week preparatory period of strength training should be long enough to show differences between training modes (e.g., Häkkinen and Komi 1981). Each strength training session was preceded by 20–30 min of low-intensity endurance exercise (below lactate threshold) and warm-up sets using lower resistance were performed prior to squat and leg press exercises. In MAX, EXP and MIX, 2–3 min of rest separated exercise sets throughout the study (Table 1). Using body weight as a load, CON completed typical circuit training including squats, push-ups, lunges, sit-ups, toe raises, back-ups, planks and step-ups in series. A work to rest ratio of 45/15 s and 50/10 s was used during weeks 0–4 and 4–8, respectively. This circuit training protocol is typical of one that an endurance runner may use. The purpose of this type of protocol is primarily to improve muscle endurance, and not maximal strength. Strength training was performed one to two times a week in all training groups and was monitored by experienced personnel so that training loads were progressively increased when necessary.

Subjects performed endurance training throughout the study. Endurance training was typically performed on

Table 1 Eight-week strength training programs

Strength training intervention programs				
	Sets	Repetitions	Load	Recovery (min)
Maximal strength				
Squat	3	4–6	80–85 % 1RM	2
Leg press	3	4–6	80–85 % 1RM	2
Calf exercise	2	12–15	50–60 % 1RM	2
Sit-ups, back-extension	3	20–30	Body weight	2
Explosive power				
Squat	3	6	30–40 % 1RM	2
Leg press	3	6	30–40 % 1RM	2
Scissor jump	2–3	10s	20 kg	2
Maximal squat jump	2–3	5 single	Body weight	2
Maximal squat jump	2–3	5 in series	Body weight[a] *(20 kg between 4 and 8)*	2
Sit-ups, back-extension	3	20–30	Body weight[a]	2
Mixed maximal strength + explosive power				
Squat and leg press (week 0–week 4):				
Warm-up	1–2	10	50–70 % 1RM	2
Maximal strength training	2	6	6RM	3
[a]Squat/Leg press (week 4–week 8):				
Warm-up	*2*	*10*	*50–70 % 1RM*	*2*
Maximal strength training	*3*	*4*	*4RM*	*3*
Box jumps	2–3	8–10	Body weight	2–3
Vertical jumps	2–3	8–10	Body weight	2–3
Sit-ups, back-extension	3	20–30	Body weight	2

The italics indicate the final four weeks of the training program (week 4–8)

[a] Modification in program during the final 4 weeks of the training intervention

non-strength training days with a training intensity below the lactate threshold (LT) throughout the study. Training intensities based on LT and respiratory compensation thresholds (RCT) were individually determined for each subject each time they were tested for maximal oxygen uptake. Subjects were informed of their individual heart rate ranges between which to train and used a heart rate monitor (Suunto t6, Vantaa, Finland) to monitor and record each training session. Training was individualized for subjects based on their training background and current fitness level; however, the relative volume and intensity were similar. Training volume (including running and "other" endurance activities) in terms of km week^{-1} was 42.6 ± 30.5, 40.7 ± 30.5, 33.0 ± 28.5 and 25.5 ± 22.0 for MAX, EXP, MIX and CON, respectively. Total endurance training time per week was 5:38 ± 0:56 h. There were no statistically significant differences in training volume. The subjects kept a training diary throughout the study, recording strength training sessions, kilometers and duration of running and "other" endurance activity (cycling, cross-country skiing and Nordic walking). Training plans were personalized based on training ability and background. Measurements took place prior to the preparatory period (for stratification into groups), before, during and after the strength training intervention (weeks 0, 4 and 8).

Measurements

Body composition

In addition to standing height (measured using standard methods), body mass and body composition were measured using bioimpedance (InBody720 body composition analyzer, Biospace Co. Ltd, Seoul, South Korea). Measurements were always taken in conjunction with blood tests between 07.30 and 08.00. Thus, subjects always arrived for testing in a fasted and rested state, helping to keep the possible confounding variables of diet and hydration status to a minimum. Subjects were measured in their underwear and were instructed to remove their watches, shoes and socks prior to measurement.

Performance measures

Aerobic capacity

Endurance performance characteristics were measured using a treadmill running protocol (Mikkola et al. 2007). The running velocity began at 8 km h^{-1} and was increased by 1 km h^{-1} every third minute until volitional exhaustion. Treadmill incline remained a constant 0.5° throughout the test. Heart rate was recorded continuously using a heart rate monitor (Suunto t6, Vantaa, Finland). The mean heart rate values from the last minute of each stage were used for analysis. Oxygen consumption was measured breath by breath throughout the test, using a portable gas analyzer (Oxycon Mobile®, Jaeger, Hoechberg, Germany). Maximal oxygen uptake $\left(\dot{V}O_{2\,\max}\right)$ was determined to the highest average 60 s $\dot{V}O_2$ value. Other factors such as heart rate, $\dot{V}O_2$ and respiratory exchange ratio were monitored for determination of maximal effort. Fingertip blood samples were taken every 3rd min to measure blood lactate concentrations. For blood sampling, the treadmill was stopped for approximately 15–20 s. Blood lactates were analyzed using a Biosen S_line Lab + lactate analyzer (EKF Diagnostic, Magdeburg, Germany). Running economy (RE) was evaluated by examining $\dot{V}O_2$ at 10 and 12 km h^{-1}, speeds comparable to the marathon running speeds of our subjects. Peak running speed (S_{peak}) was calculated as follows S_{peak} = speed of the last whole completed stage (km h^{-1}) + (running time (s) of the speed at exhaustion − 30 s)/(180 − 30 s) × 1 km h^{-1} (Mikkola et al. 2011). Lactate threshold (LT) and respiratory compensation threshold (RCT) were determined using blood lactate, ventilation, $\dot{V}O_2$ and $\dot{V}CO_2$ (production of carbon dioxide) according to Meyer et al. (2005).

Strength and power measurements

Isometric leg press

An electromechanical isometric leg extension device (designed and manufactured by the Department of Biology of Physical Activity, University of Jyväskylä, Finland) was used to measure maximal strength and rate of force development (RFD). The subjects' knee angle was 107°, while the hip angle was 110°. Subjects were instructed to produce force "as fast and as hard as possible" for approximately 3 s. Subjects performed at least three maximum voluntary contractions (Häkkinen et al. 1998). If the maximum force during the last trial was greater than 5 % compared to the previous trial, an additional trial was performed. The best performance trial, in terms of maximal force measured in newtons (N), was used for statistical analysis.

One repetition maximum

One repetition maximum (maximal dynamic bilateral horizontal leg press in a seated position) was measured using a David 210 dynamometer (David Sports Ltd., Helsinki, Finland) (Häkkinen et al. 1998). Prior to attempting

1RM, subjects completed a warm-up consisting of 5 × 70 % 1RM, 1 × 80–85 % 1RM and 1 × 90–95 % of estimated 1RM, with 1 min of rest between sets. Following this warm-up, no more than five attempts to reach 1RM were made. Leg extension action started from a knee angle of approximately 65°. Subjects were instructed to grasp handles located by the seat of the dynamometer and to keep constant contact with the seat and backrest during leg extension to a full extension of 180°. Verbal encouragement was given to promote maximal effort. The greatest weight that the subject could successfully lift (knees fully extended) to the accuracy of 2.5 kg was accepted as 1RM.

Countermovement jump

A force platform (Department of Biology of Physical Activity, Jyväskylä, Finland) was used to measure maximal dynamic explosive force in a countermovement jump (CMJ) (Bosco and Komi 1978). Subjects were instructed to stand with their feet approximately hip-width apart with their hands on their hips. Subjects were then instructed to perform a quick and explosive CMJ on verbal command, so that knee angle for the jump was no less than 90°. Force data was collected and analyzed by computer software (Signal 2.14, CED, Cambridge, UK), which used the equation $h = \mathrm{I}^2/2\ gm^2$ to calculate jump height from impulse ($I =$ impulse, $g =$ gravity and $m =$ mass of subject).

Electromyographic activity

Electromyographic activity (EMG) was recorded from the vastus lateralis (VL) and vastus medialis (VM) of the right leg during maximal isometric leg extension, 1RM and CMJ. Electrode positions were marked with small ink tattoos (Häkkinen and Komi 1983) on the skin during the first testing session to ensure that electrode placement over the entire experimental period would be consistent. The guidelines published by Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM http://www.seniam.org/) were followed for skin preparation, electrode placement and orientation. Inter-electrode distance was 20 mm (input impedance <10 kΩ, common mode rejection ratio 80 dB, 1,000 gain). Raw signals were passed from a transmitter, positioned around the subjects' waist, to a receiver (Telemyo 2400R, Noraxon, Scottsdale, AZ, USA) from which the signal was relayed to the computer via an AD converter (Micro1401, CED, Cambridge, UK). Whole range EMG was recorded from the starting knee angle of approximately 65° to full leg extension of 180° and subsequently analyzed by computer software (Signal 2.14, CED, UK).

Serum hormones

Venous blood samples (10 ml) were collected from the antecubital vein using sterile needles into serum tubes (Venosafe, Terumo Medical Co., Leuven, Belgium) by a qualified laboratory technician. Subjects were tested after 12 h of fasting between 07.30 and 08.00 and were instructed to refrain from strenuous physical activity for 24 h prior to the tests. Whole blood was centrifuged at 2500*g* (Megafuge 1.0R, Heraeus, Germany) for 10 min after which serum was removed and stored at −80 °C until analysis. Samples were used for determination of serum testosterone TESTO, CORT, TSH, DHEAS and sex-hormone binding globulin (SHBG). Analyses were performed using chemical luminescence techniques (Immunlite 1000, DCP Diagnostics Corporation, Los Angeles, California, USA) and hormone-specific immunoassay kits (Siemens, New York, NY, USA). The sensitivity of TESTO, CORT, TSH, DHEAS and SHBG assays were 0.7 nmol l^{-1}, 5.5 nmol l^{-1} 0.004 mIU l^{-1}, 0.08 μmol l^{-1} and 0.2 nmol l^{-1}, respectively. The intra-assay coefficients of variation for TESTO, CORT, TSH, DHEAS and SHBG were: 5.7, 4.6, 3.9, 9.5 and 2.4 %, respectively.

Statistical methods

Standard statistical methods were used for calculation of means, standard deviation, standard error and Pearson product–moment correlation coefficients. Group differences were analyzed using a one-way analysis of variance (one-way ANOVA) and within group differences (group-by-training interaction) were analyzed using repeated measures ANOVA. ANCOVA (using baseline measurements as a covariate) was used in analyzing CMJ due to changes in jumping height following the 6-week preparatory period. In the presence of a significant *F* value, post hoc comparison of means was provided by Fisher's LSD test. The criterion for significance was set at $* = p \leq 0.05$, $** = p < 0.01$ and $*** = p < 0.001$. Statistical analysis was completed using SPSSWIN 15.0 (SPSS Inc., Chicago, IL, USA).

Results

Maximal strength increased significantly in all experimental training groups after the first 4 weeks of the strength training intervention, while the increases in maximal strength plateaued in the final 4 weeks (Fig. 1). In the control group, maximal strength increased only slightly (n.s.) during the first 4 weeks of the strength training intervention, but a significant decrease in maximal strength was observed in the final 4 weeks (Fig. 1). Muscle

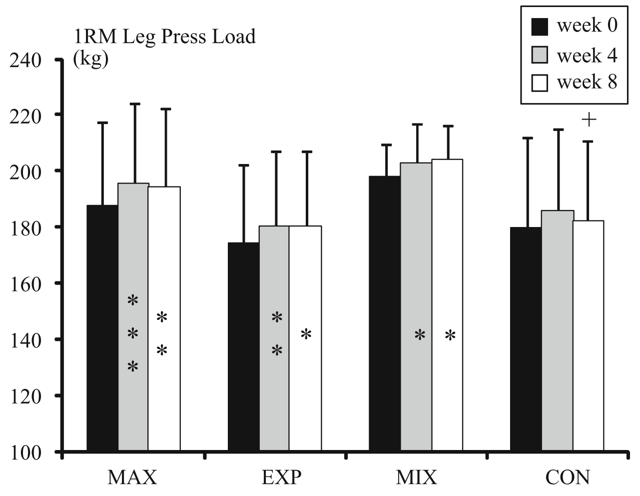

Fig. 1 Maximal strength as maximal bilateral dynamic leg press 1RM load (kg) during the 8-week strength training intervention (mean ± SD). $^{*}p \leq 0.05$, $^{**}p < 0.01$ and $^{***}p < 0.001$ from week 0 and $^{+}p \leq 0.05$ from week 4

activation of VL increased significantly only in MAX from week 0 to 8 (11.8 %, $p < 0.05$), while muscle activation as an average of VL + VM did not change significantly in any of the groups. No significant differences in maximal strength development or changes in muscle activation were observed between groups.

Maximal strength measured by maximal bilateral isometric leg press did not change significantly in any of the groups (Fig. 2). Rate of force development and muscle activation of VL and VM were also statistically unaltered during the 8-week strength training intervention. No significant differences in isometric strength and rate of force development or changes in muscle activation were observed between groups.

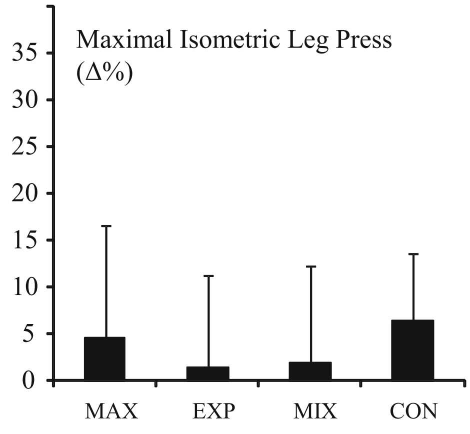

Fig. 2 Relative change (%) in maximal isometric leg press force after the 8-week strength training intervention

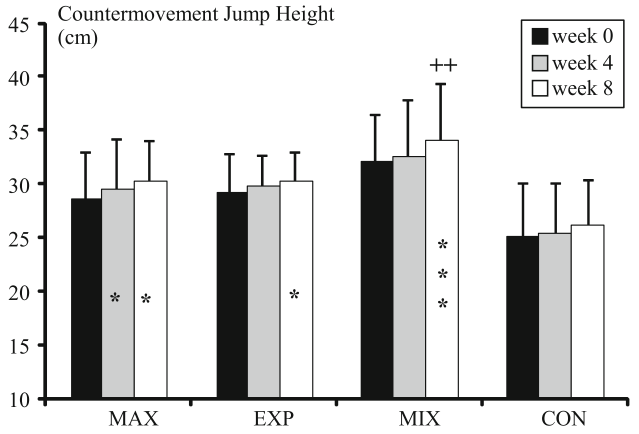

Fig. 3 Countermovement jump height (cm) during the 8-week strength training intervention (mean ± SD). $^{*}p \leq 0.05$, $^{**}p < 0.01$ and $^{***}p < 0.001$ from week 0 and, $^{+}p \leq 0.05$ from week 4

Significant increases were observed in CMJ height of all three experimental strength training groups by the end of the strength training intervention, while CON showed no changes (Fig. 3). In MAX, the significant increase in jumping height was observed already after 4 weeks of the strength training intervention, whereas in EXP and MIX, a significant increase was observed at the end of the strength training intervention (week 8). In MIX, the significant improvement in CMJ height occurred primarily in the final 4 weeks of the strength training intervention. Significant changes in muscle activation of VL and VM during CMJ were observed only in EXP (21.3 %, $p < 0.05$ between weeks 0 and 8) over the entire strength training intervention. No significant differences in countermovement jump height development or changes in muscle activation were observed between groups.

Maximal oxygen uptake ($\dot{V}O_{2\max}$ in ml kg^{-1} min^{-1}) did not change significantly in the experimental groups (MAX 51.4 ± 3.8 to 52.1 ± 4.9, EXP 50.6 ± 5.2 to 51.7 ± 4.0 and MIX 51.3 ± 5.2 to 51.7 ± 5.4), while a significant increase in $\dot{V}O_{2\max}$ was observed in the control group (47.0 ± 6.2 to 49.8 ± 7.0 $p < 0.01$). Running economy at 10 km hr^{-1} and 12 km hr^{-1} did not change in terms of ml kg^{-1} min^{-1} over the 8-week strength training intervention, while a significant increase in S_{peak} and $\text{RCT}_{\text{speed}}$ was observed in all groups (Fig. 4). No significant differences in changes of $\dot{V}O_{2\max}$, S_{peak} or $\text{RCT}_{\text{speed}}$ were observed between groups.

Body mass decreased significantly in MAX, EXP and CON, while body fat percentage did not change significantly during the 8-week strength training intervention in any group (Table 2). No significant changes were observed in changes of body mass or body fat percentage between the groups.

Serum hormone concentrations of TESTO, CORT, TSH and DHEAS did not change significantly over the 8-week strength training intervention. The serum concentration of SHBG decreased significantly in EXP from week 0 to week

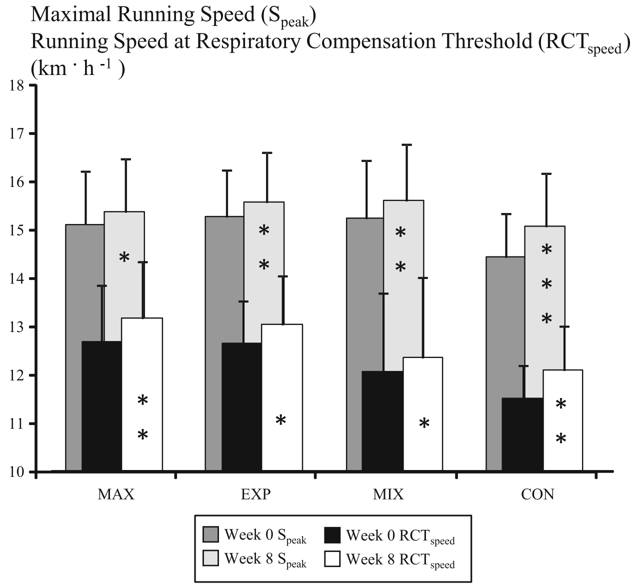

Fig. 4 Maximal running speed (S_{peak}, km hr^{-1}) and running speed at respiratory compensation threshold (RCT_{speed}, km hr^{-1}) before and after the 8-week strength training intervention (mean ± SD). $^{*}p \leq 0.05$, $^{**}p < 0.01$ and $^{***}p < 0.001$ from week 0 (lower values indicate RCT_{speed}; upper values indicate S_{peak})

Table 2 Body mass and percent fat as measured by InBody during the 8-week strength training intervention (mean ± SD)

	Week 0	Week 4	Week 8
Mass (kg)			
MAX	78.8 ± 5.9	78.3 ± 6.0	77.4 ± 5.9^{+}
EXP	78.6 ± 6.3	78.4 ± 5.7	76.9 ± 5.4^{**++}
MIX	78.4 ± 6.8	78.6 ± 7.1	78.6 ± 7.0
CON	84.3 ± 9.5	84.0 ± 9.9	82.9 ± 9.6^{*+}
Fat %			
MAX	17.2 ± 4.0	17.1 ± 4.2	16.7 ± 4.3
EXP	16.0 ± 6.1	16.0 ± 5.9	15.4 ± 5.7
MIX	16.2 ± 5.4	15.9 ± 5.5	15.8 ± 4.0
CON	20.8 ± 5.4	20.5 ± 5.7	19.8 ± 5.6

* $p \leq 0.05$ from week 0, ** $p \leq 0.01$ from week 0, $^{+}$ $p \leq 0.05$ from week 4 and $^{++}$ $p \leq 0.01$ from week 4

Table 3 Serum hormone and SHBG concentrations during the 8-week strength training intervention (mean ± SD)

	WEEK 0	WEEK 4	WEEK 8
TESTO (nmol l^{-1})			
MAX	18.7 ± 5.7	17.4 ± 5.4	17.8 ± 3.3
EXP	15.9 ± 3.7	17.1 ± 3.2	16.8 ± 3.0
MIX	23.2 ± 4.2	23.7 ± 5.0	20.1 ± 5.7*
CON	15.5 ± 4.4	15.6 ± 27	13.7 ± 3.5
CORT (nmol l^{-1})			
MAX	440.4 ± 98.1	412.8 ± 79.9	401.9 ± 94.9
EXP	414.6 ± 78.9	452.5 ± 134.5	437.6 ± 120.2
MIX	496.6 ± 148.0	542.9 ± 103.2	482.0 ± 119.2
CON	468.3 ± 118.5	497.3 ± 108.4	456.7 ± 124.7
TSH (μIU ml^{-1})			
MAX	2.2 ± 0.8	22 ± 0.8	2.0 ± 0.8
EXP	1.8 ± 0.4	2.0 ± 0.8	2.1 ± 1.0
MIX	2.3 ± 1.1	2.5 ± 1.1	2.5 ± 1.1
CON	1.9 ± 0.9	1.9 ± 0.8	1.7 ± 1.0
DHEAS (μmol l^{-1})			
MIX	6.7 ± 1.4	6.6 ± 1.5	6.7 ± 1.3
EXP	5.0 ± 1.8	5.0 ± 18	5.1 ± 1.4
MK	7.4 ± 3.7	7.2 ± 3.6	6.7 ± 3.6
CON	7.9 ± 4.8	6.4 ± 3.9	6.4 ± 4.0
SHBG (nmol l^{-1})			
MAX	39.6 ± 11.2	37.9 ± 13.4	39.7 ± 12.9
EXP	44.2 ± 14.2	41.3 ± 12.5	40.4 ± 11.3*
MIX	39.1 ± 14.7	38.2 ± 15.5	39.2 ± 16.8
CON	27.5 ± 7.4	29.0 ± 7.9	27.5 ± 7.3

* $p \leq 0.05$

8, while in MAX, MIX and CON concentrations remained statistically unaltered (Table 3). No significant changes were observed in serum hormone concentrations between the groups.

Discussion

In this study, low volume mixed maximal and explosive strength training (MIX), maximal strength training (MAX) and explosive strength training (EXP) were performed concurrently with a higher volume of endurance training over an 8-week training intervention in endurance runners. The primary findings from the intervention period showed significant increases in maximal dynamic strength (1RM), power (CMJ) and training specific maximal muscle activation in the experimental strength training groups. These neuromuscular changes were accompanied by increases in maximal running speed (S_{peak}) and running speed at respiratory compensation threshold (RCT_{speed}) without a significant change in $\dot{V}O_{2max}$ or running economy. Interestingly, these significant increases in strength and power were primarily observed during the first 4 weeks of the strength training intervention, whereas a plateau in improvements was observed in the final 4 weeks. Maximal isometric strength, rate of force development (RFD) and muscle activation during the maximal isometric leg press action remained unchanged throughout the 8-week intervention. The circuit training control group (CON) did not show significant increases in any neuromuscular performance variables, and a significant decrease in 1RM was even observed in the final 4 weeks of training. This group improved S_{peak}, $\mathrm{RCT}_{\mathrm{speed}}$ and $\dot{V}\mathrm{O}_{2\max}$, but did not improve running economy. Nevertheless, no significant differences in changes between groups were observed in any of the variables during the 8-week intervention.

The significant increases in maximal dynamic strength observed in MAX, EXP and MIX during the first 4 weeks of the strength training intervention were expected given that the subjects had no previous background in strength training aside from the 6-week period of preparatory training that they completed prior to the strength training intervention. Strength gains are known to occur relatively quickly in individuals previously untrained in strength in comparison to strength-trained individuals (Häkkinen 1985; Ahtiainen et al. 2003). It is, however, important to note that the average of 3.5 % gains in strength over the 8-week strength training intervention in the strength training groups were much smaller than those of 10–20 % (e.g., Ahtiainen et al. 2003) typically observed when heavy resistance training is performed alone. The average gains in maximal strength in the present study were also smaller than the gains of about 10 % observed after approximately 8 weeks of concurrent heavy resistance and bicycle endurance training in untrained men (e.g., Häkkinen et al. 2003). A plateau in maximal strength gains was observed in the final 4 weeks of the strength training intervention. While a plateau may typically be expected to occur later, the present 6-week preparatory strength training period did use relatively high loads of 50–70 % 1RM combined with endurance training, which induced small learning-related changes while preparing subjects for the strength training intervention. Therefore, by the end of the first 4 weeks of the actual strength training intervention, it is important to note that subjects had completed a total of 10 weeks of strength training. Previous studies of combined strength and endurance training (e.g., Hickson 1980; Hunter et al. 1987) have also shown plateaus in strength development after the initial weeks of training, while other studies have reported continued strength development over a longer periodized training period (e.g., Häkkinen et al. 2003; Karavirta et al. 2009). Most of the studies reporting a plateau in strength development have included a higher volume of progressive combined strength and endurance training (e.g., Hickson 1980) and a plateau could be observed already after 6–8 weeks of training. The strength training stimuli progressively of one to two times a week in the present study may not have been strong enough to stimulate continuous improvements in maximal strength in the groups performing endurance training concurrently at a relatively higher frequency of three to four times per week. It is of particular interest that the final 4 weeks of the strength training intervention showed a significant decrease in 1RM of CON. This decrease suggests that the circuit training stimulus, combined with endurance training, was not enough to maintain maximal strength. It is important to note that all three experimental strength training modes, when combined with endurance training, were more effective in improving strength and power than combined circuit training and endurance training, though caution should be exercised with the interpretation of these results as no strength training only group was included in the present experimental design.

Although each of the three strength training groups showed significant strength gains, no significant differences were observed between the three experimental groups with regard to strength development. Eight weeks of low frequency strength training, when accompanied by a higher frequency of endurance training, may not be adequate to show the potential differences in absolute strength and power development that may be expected. Additionally, differences in adaptations to maximal or explosive strength training regimens may not be observed until after 8–12 weeks of specific strength training (Häkkinen 1994). The similar increases in maximal strength of MAX, EXP and MIX may, in this case, be explained by the same mechanisms, because gains in maximal strength are typically associated with increased muscle activation in early-phase adaptations that are followed by muscle hypertrophy (Häkkinen 1985, 1994). Naturally, one would expect maximal strength training to improve maximal strength, but explosive strength training can also cause some initial gains in maximal strength (Häkkinen et al. 1985). The improvements in muscle activation that were observed in MAX during dynamic 1RM and in EXP during CMJ may be indicators of these early-phase adaptations specific to the respective maximal and explosive strength training modes. It is worth noting that other muscles/groups of muscles may have influenced strength and power development and possibly contributed to the development of endurance performance parameters measured in this study. Muscle hypertrophy was not taken into account in this study, but our previous study (e.g., Taipale et al. 2010) indicates that small, but significant gains in the cross-sectional area of the trained muscles can be achieved even when maximal strength training is combined with endurance training.

It was interesting to observe that maximal isometric strength, RFD and muscle activation of the trained muscles during maximal isometric force production did not change in any of the groups. Percent increases in isometric strength are typically smaller than those observed in dynamic strength. Thus given that the percent increases in maximal dynamic strength in the present study were markedly smaller than those is studies involving strength training alone, we suspect that the isometric leg press measurement was not sensitive enough to measure the smaller changes in force production induced by combined training. This seems to be true especially in the case of maximal isometric force, since Paavolainen et al. (1991, 1999) found that explosive strength training in endurance athletes positively influenced measures of performance including RFD (Paavolainen et al. 1991), but maximal isometric force did not change significantly. Many other studies examining combined strength and endurance training in non-athlete populations have used cycling as their endurance training method and seem to show greater increases in both dynamic and isometric strength of the lower extremities than the present study (e.g., Karavirta et al. 2009, Häkkinen et al. 2003). The greater increase in dynamic and isometric strength likely results, in part, from the differences in force production between the two training modes of running and bicycling, e.g., leg extensors produce a large amount of force during the concentric phase in cycling, whereas running is characterized by a rapid and repetitive stretch–shortening cycle action. It should also be noted that in cycling, the quadriceps femoris and gluteus muscles play a more significant role than in running where the biceps femoris also does significant work (Kyröläinen et al. 2001).

Countermovement jump height increased in MAX, EXP and MIX, but not in CON. The improvement in jumping height was particularly noticeable in MIX and occurred primarily during the final 4 weeks of the strength training intervention. It has previously been reported that maximal strength must be adequate for improvements in explosive power to occur (Newton and Kraemer 1994). Thus, it is possible that that the combination of maximal strength training and explosive power training helped to develop maximal strength to a level that subsequently “allowed” for gains in explosive power, whereas maximal strength training and explosive power training alone did not provide enough training “diversity”.

The lack of specific differences in the development of neuromuscular characteristics in the present study may be related to the fact that our subjects were untrained in terms of strength prior to this study. Cormie et al. (2010) found that improvements in athletic performance were similar over 10 weeks of training in untrained men performing either strength or ballistic power training, though it was noted that there were some differences in the mechanisms driving improvements. This appears to be in line with our findings as the magnitude of improvements in 1RM and CMJ are similar despite the different strength training regimens performed. Muscle activation during the 8-week training period improved significantly in MAX during dynamic 1RM, while muscle activation in EXP improved during CMJ which may suggest some specificity of training. Although no significant improvements in muscle activation were observed in MIX, the improvement in activation of other leg muscles cannot be entirely ruled out.

Only minor (n.s.) changes were observed in $\dot{V}O_{2max}$ of MAX, EXP and MIX, while a significant increase in $\dot{V}O_{2max}$ was observed in CON. Large changes in $\dot{V}O_{2max}$ were not expected in any group during this 8-week study period, as endurance training volume was relatively low and training intensity was primarily below LT. While intermittent high-intensity endurance training (such as interval training) can increase $\dot{V}O_{2max}$ when performed three times a week over 8 weeks, low-intensity endurance training does not significantly influence endurance performance in terms of $\dot{V}O_{2max}$ (Helgerud et al. 2007). The significant improvement observed in $\dot{V}O_{2max}$ of CON may be attributed to circuit training, which essentially added an extra 1.5 training sessions per week of endurance training to the three to four times per week of endurance training. Changes in other endurance performance parameters such as S_{peak} and running economy, however, may be positively influenced by low-intensity endurance training (Billat and Koralsztein 1996). Although $\dot{V}O_{2max}$ has long been reported to be the most important determinant of endurance performance, the value of S_{peak} combines $\dot{V}O_{2max}$ and running economy into a single factor (Billat and Koralsztein 1996) which has been shown to predict performance in 10–90 km races (Noakes et al. 1990). The increase in S_{peak} and RCT_{speed} in all strength training groups suggests improved endurance performance despite the fact that there were no changes in $\dot{V}O_{2max}$ or running economy during the 8-week training intervention. While endurance performance measured by S_{peak} and RCT_{speed} improved to a similar extent in all three strength training groups as well as the circuit training control group, we cannot exclude the possibility that a difference in adaptations might be observed in the weeks following the actual strength training intervention. Improved muscle strength and power may be beneficial in subsequent endurance training when athletes try to maximize their endurance performance characteristics. For example, when strength training volume is decreased and endurance volume is increased following 8 weeks of MAX or EXP training, we have previously found that MAX appears better prepared to tolerate the increased endurance volume and make use of neuromuscular adaptations to improve endurance performance including running economy and maximal running speed (Taipale et al. 2010).

Basal serum levels of CORT, TSH and DHEAS did not fluctuate significantly during the 8-week strength training intervention, while between weeks 0 and 8 serum TESTO decreased in MIX and serum SHBG decreased in EXP. The overall training stimuli in this investigation may not be “strong” enough to induce hormonal changes in all groups in this relatively short period of time, though other studies from our laboratory have shown significant changes in the TESTO to CORT ratio over a more prolonged period of combined training (Taipale et al. 2010). The observed decreases in TESTO in MIX and SHBG in EXP may indicate some level of stress, overreaching or possibly interference. Untrained individuals may be more susceptible to training stress than trained individuals and this may be reflected in serum hormone concentrations. Previous research suggests that lesser improvements in strength in combined training may also be related to an elevated catabolic state which could influence, e.g., muscle hypertrophy (Kraemer et al. 1995; Bell et al. 2000).

In the present study, mixed maximal and explosive strength training, maximal strength training and explosive strength training were performed concurrently with endurance training over an 8-week training intervention and were "more effective" during this period than circuit training in increasing and maintaining maximal strength and explosive power. The three groups performing a low volume of strength training did not, however, differ from each other with regard to strength and power improvements while concurrently performing a higher volume of endurance training. While all groups made significant gains in the important performance measures of S_{peak} and RCT_{speed}, there may be additional benefits to increased maximal strength, power and muscle activation over a more prolonged period of time including, e.g., improved movement economy and S_{peak} (Taipale et al. 2010). Improvements in strength and power appear to be highly individual, thus performing the more diverse mixture of maximal and explosive strength training in a way that meets individual needs may be more effective than maximal or explosive strength training combined with endurance training alone.

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