

# Strength Training in Endurance Runners

## Authors

R. S. Taipale<sup>1</sup>, J. Mikkola<sup>2</sup>, A. Nummela<sup>2</sup>, V. Vesterinen<sup>2</sup>, B. Capostagno<sup>3</sup>, S. Walker<sup>1</sup>, D. Gitonga<sup>1</sup>, W. J. Kraemer<sup>4</sup>, K. Häkkinen<sup>1</sup>

## Affiliations

Affiliation addresses are listed at the end of the article

## Key words

- concurrent training
- neuromuscular performance
- endurance performance
- running economy
- strength

## Abstract

▼ This study examined effects of periodized maximal versus explosive strength training and reduced strength training, combined with endurance training, on neuromuscular and endurance performance in recreational endurance runners. Subjects first completed 6 weeks of preparatory strength training. Then, groups of maximal strength (MAX, n=11), explosive strength (EXP, n=10) and circuit training (C, n=7) completed an 8-week strength training intervention, followed by 14 weeks of reduced strength training. Maximal strength (1RM) and muscle activation (EMG) of leg extensors, countermovement jump (CMJ), maximal oxygen uptake (VO<sub>2MAX</sub>), velocity at VO<sub>2MAX</sub> (vVO<sub>2MAX</sub>) running economy (RE) and

basal serum hormones were measured. 1RM and CMJ improved (p<0.05) in all groups accompanied by increased EMG in MAX and EXP (p<0.05) during strength training. Minor changes occurred in VO<sub>2MAX</sub>, but vVO<sub>2MAX</sub> improved in all groups (p<0.05) and RE in EXP (p<0.05). During reduced strength training 1RM and EMG decreased in MAX (p<0.05) while vVO<sub>2MAX</sub> in MAX and EXP (p<0.05) and RE in MAX (p<0.01) improved. Serum testosterone and cortisol remained unaltered. Maximal or explosive strength training performed concurrently with endurance training was more effective in improving strength and neuromuscular performance and in enhancing vVO<sub>2MAX</sub> and RE in recreational endurance runners than concurrent circuit and endurance training.

## Introduction

▼ Strength and endurance training are commonly known to produce divergent adaptations. The primary adaptation to endurance training is improved oxygen transportation and utilization by way of increased capillary and mitochondrial density, as well as increased enzyme activity, which improves oxidative energy metabolism [3, 13]. The primary adaptation to strength training with high loads includes increases in maximal strength, resulting from improvements in voluntary neuromuscular activation, which is usually followed by muscle hypertrophy during prolonged training periods [18]. Unlike strength training, endurance running requires only repetitive low force production, and even intensive uphill running does not induce maximal activation of the leg muscles [38]. Nevertheless, even in endurance sports, strength training for increases in strength and power has been reported to be beneficial in leading to increases in rapid force production e.g. contributing to increases in run-

ning speed. Thus, regardless of the divergent adaptations of strength and endurance training, recreational and elite endurance athletes may perform both types of training concurrently to optimize endurance performance.

Many different models exist for periodization of resistance training, particularly when it is performed concurrently with endurance exercise. Endurance runners often include either very little or no resistance training in their exercise programs, especially when increases in running volume occur, which makes the periodization of concurrent strength and endurance training in endurance runners very different from that of strength and power athletes. Periodized training typically calls for periods of higher intensity/volume of training alternated with periods of lower intensity/volume of training. The periods of lower intensity/volume of training may not provide an adequate training stimulus for development, or even maintenance of strength, a phenomenon referred to as “detraining”. Detraining from strength training is further characterized by

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## Bibliography

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## Correspondence

**Ritva S Taipale**  
University of Jyväskylä  
Department of Biology of  
Physical Activity  
P.O. Box 35 (VIV)  
40014 Jyväskylä  
Finland  
Tel.: +358142602089  
Fax: +358142602071  
ritva.taipale@jyu.fi

decreases in strength, muscle mass, and muscle activation [19] that mirrors the time-course of the preceding training adaptations [31].

It has been suggested that endurance training may interfere with strength development when strength and endurance training are performed concurrently [4,14,31]. When present, this interference effect is predominantly attributed to a high volume of training, high intensity training or prolonged training duration [4, 14, 22], and may also be related to hormonal adaptations, mechanical stress, and muscle damage [4,24]. It might be hypothesized that changes in concentrations of the hormones of testosterone and cortisol also play a role in this interference effect. Strength exercise typically stimulates an acute increase in testosterone [25], associated with anabolic processes in the body such as muscle growth. In contrast, a chronic increase in circulating basal levels of cortisol, indicating an increase in catabolic activity, has been reported with prolonged endurance training [41].

Several studies have shown increases in endurance performance resulting from the addition of various types of strength training to endurance training regimens in endurance runners (orienteers) [34] cross-country skiers [15,27], triathletes [29] and previously untrained men [16,22]. These studies have examined maximal or explosive strength training combined with endurance training, but no studies have been conducted to compare these two different strength training modes when they are combined with endurance training. Improvements in endurance performance in the previously mentioned studies have been attributed to enhanced neuromuscular activation and improved sport-specific economy rather than increases in maximal oxygen uptake ( $VO_{2max}$ ). Moreover, individual performance differences can be further explained by running speed at  $VO_{2max}$  ( $vVO_{2max}$ ) which is often used in the analysis of distance running performance, and for monitoring training [5].

The primary purpose of the present study was to examine the effects of periodized maximal versus explosive strength training, combined with endurance training, on neuromuscular adaptations and changes in endurance performance in male recreational endurance runners. In addition, this study examined the effect of reduced strength training volume, accompanied by increased endurance training volume, on strength maintenance and endurance performance.

## Methods

### ▼

#### Subjects

A total of twenty-eight male recreational endurance runners (age 21–45 years) were recruited from the region as part of a marathon training school, and completed the study. Subjects were fully informed about the study design, including information on the possible risks and benefits of participation, prior to 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 as well as the standards of the International Journal of Sports Medicine [12]. Most of the subjects had previously completed either a running marathon or half-marathon. Subjects were divided into three groups matched for age, anthropometrics, training experience, strength and  $VO_{2max}$  following baseline testing at –6 weeks. Groups included a maximal strength training group (MAX,  $n=11$ , age:  $35.5 \pm 5.8$  years, height:  $178.6 \pm 4.6$  cm (mean  $\pm$  SD)), an explosive strength training group (EXP,  $n=10$ ,  $36.4 \pm 6.1$  years,  $180.5 \pm 6.1$  cm) and a circuit training control group that acted as a control and used only their own body weight as a load following the preparatory period (C,  $n=7$ ,  $33.7 \pm 8.2$  years,  $180.0 \pm 4.5$  cm). Subjects were not using medications nor did they have any injuries that would affect physical performance. Following the period of reduced strength training and increased endurance training, 2 subjects from the circuit training group were unable to complete all testing due to minor injuries; thus, statistics following this period are calculated separately.

#### Study design and training

Strength training throughout the 28-week study was focused on the leg extensors, a major muscle group at work in human locomotion and in running, and was preceded by 20–30 min of low-intensity endurance exercise (below aerobic threshold) [2]. The preparatory strength training period consisted of approximately 9 training sessions completed over 6 weeks in which all subjects performed strength training exercises using loads that progressed from 50 to 70% 1RM, and that were similar to those used in the training intervention (see Table 1). The preparatory period was followed by an 8-week strength training intervention in which groups began their specified maximal, explosive or circuit training programs, and in which strength training was to be

**Table 1** Periodized strength training programs over 28 weeks of training.

6-week preparatory strength training period	8-week strength training intervention	14-week reduced volume strength training period
<b>Maximal Strength Training</b>		
– 2–3 sets, 10–15 $\times$ 50–70% 1RM squat/leg press, knee extension, knee flexion, lat pull-down/bench press, calf exercises and countermovement jump	– 3 sets, 4–6 $\times$ 80–85% 1RM squats (Smith) and leg press – 2 sets, 12–15 $\times$ 50–60% 1RM calf exercise	– 3 sets, 6–8 $\times$ 75–80% 1RM squats (Smith) – 2 sets, 10–12 $\times$ 60–70% 1RM knee extension, knee flexion, lat pull-down, calf exercises and bench press
<b>Explosive Strength Training</b>		
– 2–3 sets, 10–15 $\times$ 50–70% 1RM squat/leg press, knee extension, knee flexion, lat pull-down/bench press, calf exercises and countermovement jump	– 3 sets, 6 $\times$ 30–40% 1RM explosive squats (Smith) and leg press – 2–3 sets, 10 s scissor jump with 20 kg load – 2–3 sets 5 maximal individual squat jumps – 2–3 sets 5 maximal squat jumps (in series) (20 kg load between 4 and 8)	– 3 sets, 6 $\times$ 30–40% 1RM explosive squats (Smith) – 3 sets, 10 s scissor jump with 20 kg load – 3 $\times$ 5 maximal squat jumps (in series) – 2 sets, 10–12 $\times$ 60–70% 1RM lat pull-down, calf exercises and bench press
<b>Circuit Training Group</b>		
– 2–3 sets, 10–15 $\times$ 50–70% 1RM squat/leg press, knee extension, knee flexion, lat pull-down/bench press, calf exercises and countermovement jump	– 3 sets, 40–50 s of: Squats, push-ups, lunges, sit-ups, calf-raises, back	– 3 sets, 50 s of: squats, push-ups/bench press, lunges, sit-ups, calf-raises, back extensions, planks and step-ups

**Table 2** Average strength and endurance training sessions per week over 28 weeks of training.

Group		6-week preparatory strength training period	8-week Strength Training Intervention		14-week reduced volume strength training period
		-6	Week 0 to Week 4	Week 4 to Week 8	+ 14 Weeks
maximal	strength	1.4±0.0	1.7±0.1**	1.6±0.1**	0.6±0.1***,+++,###
	endurance	3.3±0.2	3.1±0.2	2.9±0.2	3.6±0.2
explosive	strength	1.4±0.1	1.7±0.1**	1.7±0.0***	0.5±0.1***,+++,###
	endurance	3.9±0.2	3.7±0.3	3.1±0.2**	3.7±0.2 <sup>§</sup>
circuit	strength	1.0±0.7	1.3±0.2	1.3±0.4	0.5±0.1
	endurance	3.7±0.4	3.1±0.6	3.0±0.7	3.6±0.5

means ± SE, \* = significant difference from -6 weeks, † = significant difference from strength training intervention week 0–week 4, ‡ = significant difference from strength training intervention week 4–week 8 (‡ = p < 0.05, \*\* = p < 0.01, \*\*\* = p < 0.001, ### = p < 0.001)

**Table 3** Average endurance training volume in kilometers per week over 28 weeks of training and average endurance training volume in hours:minutes per week.

Group		6-week preparatory strength training period	8-week strength training intervention		14-week reduced volume strength training period
		-6 weeks	week 0 to week 4	week 4 to week 8	+ 14 weeks
maximal	running km	19.0±2.8	22.2±2.5	30.3±4.5*	38.1±3.4***,+++,#
explosive	running km	23.5±5.6	26.0±4.6	38.3±4.8***,††	40.8±5.6***,††
circuit	running km	21.5±4.1	20.0±5.0	29.8±7.8	36.4±5.3***,††

means ± SE, \* = significant difference from -6 weeks, † = significant difference from strength training intervention week 0–week 4, ‡ = significant difference from strength training intervention week 4–week 8, § = significant difference from 8-week training intervention (\*, ‡ = p < 0.05, †† = p < 0.01, \*\*\* = p < 0.001)

completed approximately twice per week (◻ **Table 2**). No statistically significant differences in training frequency were observed between training groups. In MAX and EXP, two to three minutes of rest separated exercise sets throughout the study. C completed exercises in series including 10–15 s of rest in between each exercise.

Throughout the study, subjects concurrently performed endurance training, typically on non-strength training days. During the preparatory period and strength training intervention, endurance training in all groups was primarily performed below the aerobic threshold, which was individually determined for each subject each time they were tested for maximal oxygen uptake. Endurance training volume during the preparatory period was at its lowest in the study in terms of both running kilometres (km) (◻ **Table 3**) and endurance training time (average hours: min ± SD, 3:02 ± 0:51, 3:45 ± 2:19, 2:34 ± 0:46 for MAX, EXP and C, respectively). Training volume, in terms of time, increased (p < 0.01 in MAX, p = 0.056 (n.s) in EXP and p = 0.128 (n.s.) in C) from the preparatory period into the actual 8-week strength training intervention (up to 4:49 ± 1:27, 4:43 ± 1:57, 4:03 ± 2:01 hours:min). In terms of running km, training volume increased from the beginning of the study to the end of the strength training intervention in all groups, although significantly only in MAX and EXP (◻ **Table 3**). There were no group differences in training volume (time or km) in these two periods. Endurance training consisted primarily of running, but also occasionally included typical outdoor activities in Finland such as cross-country skiing, cycling and Nordic walking. This “other training” ranged an average of 6 to 15 km/week throughout the entire experimental period.

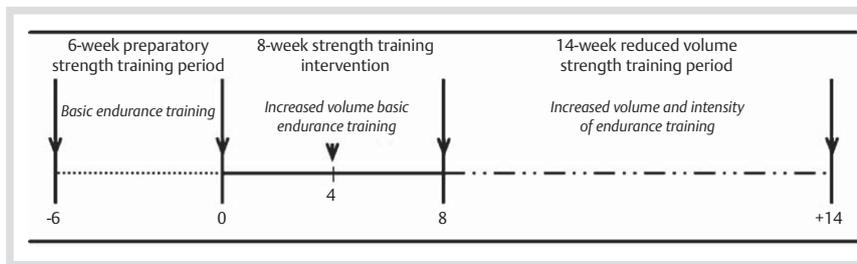
Following the main training periods, including the preparatory training period and strength training intervention, a 14-week reduced strength and increased endurance training period was completed as part of marathon preparation. Subjects completed strength training ≤ 1 time per week for 14 weeks (◻ **Table 2**) for strength maintenance purposes. At this time, running volume in

km increased significantly in all groups (◻ **Table 3**). Endurance training volume in time during this period was 5:20 ± 1:36, 4:52 ± 1:41, 4:50 ± 1:29 (hours:min) in MAX, EXP and C, respectively. From the beginning of the study to the end of the study, this increase in running volume was significant (p < 0.05) in all three training groups. No statistical differences in training volume either in terms of km or time of endurance training between groups were observed during this 14-week period. Intensity of endurance training was at its highest during this period including training sessions that were performed above aerobic or anaerobic thresholds. In addition, longer lower intensity training sessions were included as part of marathon preparation. Subjects kept a training diary throughout the study recording strength training sessions, weekly kilometres of running and “other” endurance activity (cycling, cross-country skiing and Nordic walking). Training plans were personalized based on training ability and background and were furthermore adjusted after each aerobic testing session (-6 weeks, weeks 0 and 8). Measurements took place prior to the preparatory period (-6 weeks), before, during and after the strength training intervention (weeks 0, 4 and 8) and after the reduced strength training period (+ 14 weeks) (◻ **Fig. 1**).

## Measurements

### Body composition

In addition to standing height, body mass and body composition were measured using bioimpedance (In body 720 body composition analyzer, Biospace Co. Ltd, Seoul, South Korea). Measurements were always taken in conjunction with blood tests between 07.30–08.00. Thus, subjects always arrived for testing in a fasted state helping to keep the possible confounding variables of diet and hydration status to a minimum. Subjects were instructed to remove excess clothing, watches, jewellery, shoes and socks prior to the measurement.



**Fig. 1** Study design including three training periods and five sets of measurements (denoted by arrows).

### Muscle thickness

Muscle thickness of vastus lateralis (VL) and vastus intermedius (VI) were measured using a compound ultrasound scanner (Aloka SSD-2000, Aloka Co., Tokyo, Japan) [17]. The subject's legs were secured with a belt at the ankles and the knees were supported with a foam pad to avoid movement during the measurements. Thickness was measured at a point marked with an ink tattoo (similar to EMG placement) that was placed on the anterior surface of the leg at 50% length of the femur measured from the lateral aspect of the distal diaphysis to the greater trochanter [39]. All measurements were performed by the same individual. Water soluble transmission gel was used to avoid unnecessary tissue compression by the probe, and the probe was adjusted manually until a clear image was achieved. Muscle thickness was calculated from the average of three consecutive muscle thickness measurements (VL+VI).

### Performance Measures

#### Aerobic capacity

Endurance capacity was measured by maximal oxygen uptake ( $VO_{2max}$ ) using a treadmill running protocol [28]. The running velocity began at  $8 \text{ km} \cdot \text{h}^{-1}$  and was increased by  $1 \text{ km} \cdot \text{h}^{-1}$  every third minute until volitional exhaustion. Treadmill incline remained a constant 0.5 degrees throughout the test. Heart rate was recorded continuously using a heart rate monitor (Suunto t6, Vantaa, Finland). 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) and  $VO_{2max}$  was accepted as the highest average 60s  $VO_2$  value. Fingertip blood samples were taken every 3rd minute to measure blood lactate concentrations. For blood sampling, the treadmill was stopped for approximately 15–20s. Blood lactates were analysed using a Biosen S\_line Lab+ lactate analyzer (EKF Diagnostic, Magdeburg, Germany). Running economy (RE) was evaluated by examining  $VO_2$  at 10 and  $12 \text{ km} \cdot \text{h}^{-1}$ , speeds comparable to the marathon running speeds of our subjects. The velocity of running at  $VO_{2max}$  ( $vVO_{2max}$ ) was calculated as follows  $vVO_{2max} = \text{speed of the last whole completed stage } (\text{km} \cdot \text{h}^{-1}) + (\text{running time (s) of the speed at exhaustion} - 30\text{s}) / (180 - 30\text{s}) * 1 \text{ km} \cdot \text{h}^{-1}$ . Aerobic (AerT) and anaerobic (AnT) thresholds were determined using blood lactate, ventilation,  $VO_2$  and  $VCO_2$  (production of carbon dioxide) according to Aunola and Rusko [2].

### Strength and Power Measurements

#### 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) [21]. Prior to attempting 1RM, subjects completed a warm-up consisting of  $5 \times 70\%$  1RM,  $1 \times 80\text{--}85\%$  1RM and  $1 \times 90\text{--}95\%$  of estimated 1RM, with one minute of rest between sets. Following this warm-up, no more than 5 attempts to reach 1RM were made. Leg extension action started from a knee angle of  $65.4 \pm 1.5$  degrees. 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 degrees. 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 by countermovement jump height [7]. 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 countermovement jump on verbal command so that knee angle for the jump was no less than 90 degrees. Force data was collected and analysed by computer software (Signal 2.14, CED, Cambridge, UK), which used the equation  $h = I^2 / 2gm^2$  to calculate jump height from impulse ( $I = \text{impulse}$ ,  $g = \text{gravity}$  and  $m = \text{mass of subject}$ ).

#### Electromyographic activity

Electromyographic activity (EMG) was recorded from the vastus lateralis (VL) and vastus medialis (VM) of the right leg during 1RM. Electrode positions were marked with small ink tattoos [19] 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 SENIAM [37] were followed for skin preparation, electrode placement and orientation. Inter-electrode distance was 20mm (input impedance  $< 10 \text{ k}\Omega$ , common mode rejection ratio 80dB, 1000 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 (Micro 1401, CED, Cambridge, UK). Whole range EMG was recorded from the starting knee angle between  $65.4 \pm 1.5$  degrees to full leg extension of 180 degrees, and subsequently analysed by computer software (Signal 2.14, CED, UK).

#### Serum hormones

Venous blood samples (10ml) were collected using sterile needles into serum tubes (Venasafe, Terumo Medical Co., Leuven, Belgium) by a qualified lab technician. Subjects were tested after 12h of fasting between 07.30–08.00. Whole blood was centrifuged at 3500rpm (Megafuge 1.0R, Heraeus, Germany) for

10min after which serum was removed and stored at  $-80^{\circ}\text{C}$  until analysis. Samples were used for determination of serum testosterone and serum cortisol. The ratio of testosterone and cortisol (testosterone/cortisol) was also calculated. Analyses were performed using chemical luminescence techniques (Immunitel 1000) and hormone specific immunoassay kits (Siemens, New York, NY, USA). The sensitivity of testosterone and cortisol assays were  $0.05\text{ nmol}\cdot\text{l}^{-1}$  and  $5.5\text{ nmol}\cdot\text{l}^{-1}$ , respectively. The intra-assay coefficients of variation for testosterone and cortisol were 3.9% and 4.6%, respectively. The inter-assay coefficients for testosterone and cortisol were 2.2% and 7.6%, respectively.

**Statistical methods**

Standard statistical methods were used for calculation of means, standard deviation (SD) and standard error (SE). Group differences were analysed using a one-way analysis of variance (One-way ANOVA) and within group differences (group-by-training interaction) were analysed using repeated measures ANOVA. 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 with SPSSWIN 15.0 (SPSS Inc., Chicago, IL, USA).

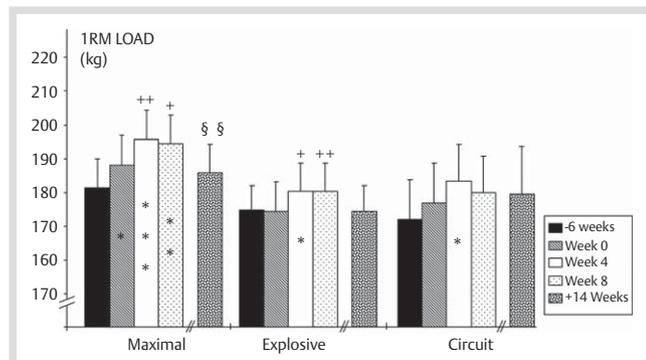
**Results**

Significant gains in 1RM were observed after the preparatory period in MAX ( $p<0.05$ ), but not in EXP or C (Fig. 2). During the strength training intervention between weeks 0 and 4, significant gains were observed in MAX and EXP ( $p<0.01$  and  $p<0.05$ , respectively) after which strength gains plateaued. Following reduced strength training, progressive decreases in strength were observed, but this decrease was significant only in MAX ( $p<0.01$ ).

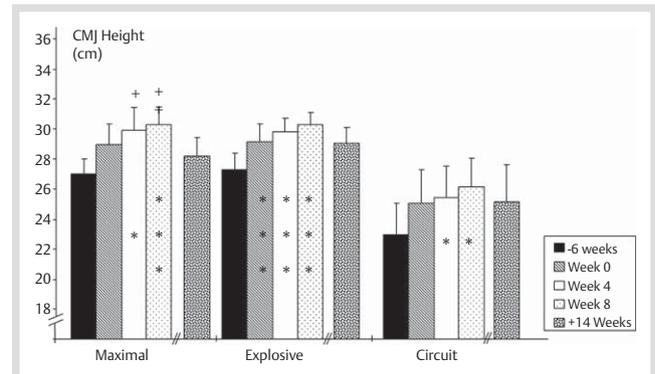
Increases in muscle activation of VL were significant from weeks -6 to 8 in MAX and EXP ( $p<0.05$  and  $p<0.01$ , respectively) (Fig. 3). Activation of VM also increased significantly over the preparatory period and the strength training intervention in MAX and in EXP (results not shown,  $p<0.05$  and  $p<0.01$ , respectively). A significant decrease in muscle activation of VL was observed in MAX after the period of reduced strength training and increased endurance training volume ( $p<0.05$ ) (Fig. 3). No significant changes in muscle activation were observed in either VL or VM in C.

Jump height improved significantly over the preparatory period and the strength training intervention in MAX, EXP and C ( $p<0.001$ ,  $p<0.001$  and  $p<0.05$ , respectively) (Fig. 4). During the strength training intervention; however, significant gains were only observed in MAX ( $p<0.05$ ). A plateau in jump height was observed in MAX and C after week 4 and in EXP after week 0.

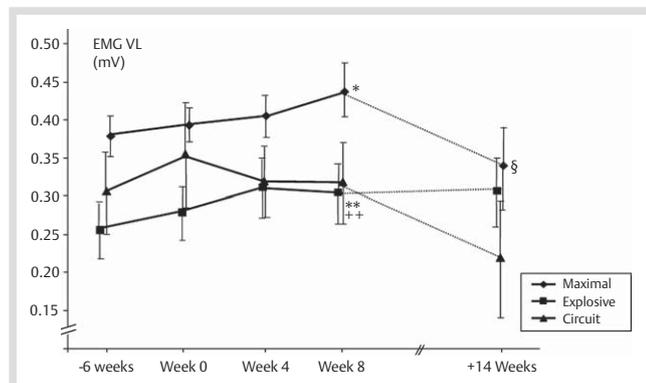
Body mass at the beginning of the experimental period was  $77.2\pm 5.5\text{ kg}$  in MAX,  $78.4\pm 6.3\text{ kg}$  in EXP, and  $83.8\pm 10.5\text{ kg}$  in C.



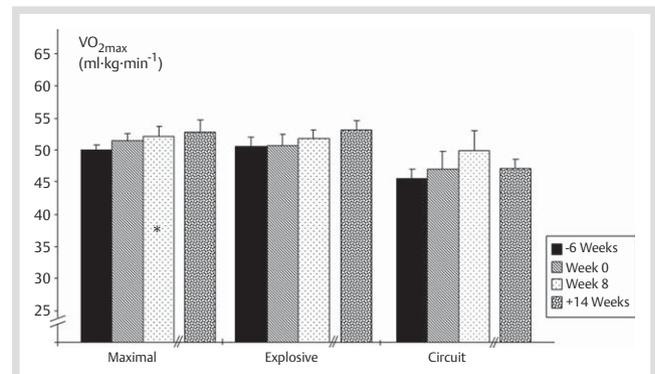
**Fig. 2** Absolute 1RM load (mean  $\pm$  SE) over 28 weeks of training. \* = significant difference from -6 weeks, + = significant difference from week 0, § = significant difference from week 8 (\*, + =  $p<0.05$ , \*\*, + +, §§ =  $p<0.01$ , \*\*\* =  $p<0.001$ ).



**Fig. 4** CMJ jump height over 28 weeks of training (mean  $\pm$  SE). \* = significant difference from -6 weeks, + = significant difference from week 0 (\*, + =  $p<0.05$ , \*\*\* =  $p<0.001$ ).



**Fig. 3** EMG of VL during 1RM over 28 weeks of training (mean  $\pm$  SE). \* = significant difference from -6 weeks, + = significant difference from week 0, § = significant difference from week 8 (\*, § =  $p<0.05$ , \*\*, + + =  $p<0.01$ ).



**Fig. 5** Maximal oxygen uptake (mean  $\pm$  SE) measured at -6 weeks, weeks 0, 8 and +14. \* = significant difference from -6 weeks (\* =  $p<0.05$ ).

A small but significant increase in body mass was observed in MAX (1.4%,  $p < 0.01$ ) after 10 weeks of training (at week 4) which was accompanied by a significant increase in muscle thickness of VL+VI (6.7%,  $p < 0.001$ ). Body mass then decreased significantly during the final 14 weeks of training (-1.6%,  $p < 0.05$ ) though no significant changes in body fat % or muscle thickness were observed. In EXP, body mass decreased significantly over both strength training periods (-2.0%,  $p < 0.05$ ) which was accompanied by a significant decrease in body fat % that occurred during the preparatory period (-7.0%,  $p < 0.01$ ). Following reduced strength training, only a significant decrease in muscle thickness was observed (-5.3%,  $p < 0.05$ ). Body mass and muscle thickness of C remained statistically unaltered throughout the study while % body fat decreased significantly over both strength training periods (-6.5%,  $p < 0.05$ ).

Maximal oxygen uptake ( $VO_{2max}$ ) improved progressively in all groups; however, significant improvement was observed only between weeks -6 and 8 in MAX (Fig. 5).

Maximal running speed at exhaustion ( $vVO_{2max}$ ) improved progressively throughout the study from week -6 to the end of the strength training intervention (week 8) in MAX, EXP and C ( $p < 0.01$ ,  $p < 0.001$  and  $p < 0.05$ , respectively) (Fig. 6). Significant increases were also observed after reduced strength training in MAX,  $p < 0.001$  and in EXP and  $p < 0.05$ , whereas in C,  $vVO_{2max}$  was statistically unaltered.

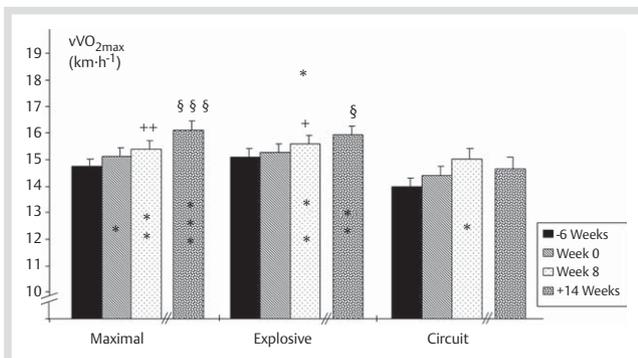
Significant improvements in running economy (RE) occurred at  $10 \text{ km} \cdot \text{h}^{-1}$  over the entire study from week -6 to +14 ( $p < 0.01$ ) in MAX while in EXP, these improvements occurred only from week -6 to 8 ( $p < 0.05$ ) (Fig. 7). Significant improvements in RE also occurred at  $12 \text{ km} \cdot \text{h}^{-1}$  in MAX over the entire study from week -6 to +14 ( $p < 0.01$ ), but not in EXP (results not

shown). No significant improvements in RE were observed in C at either speed.

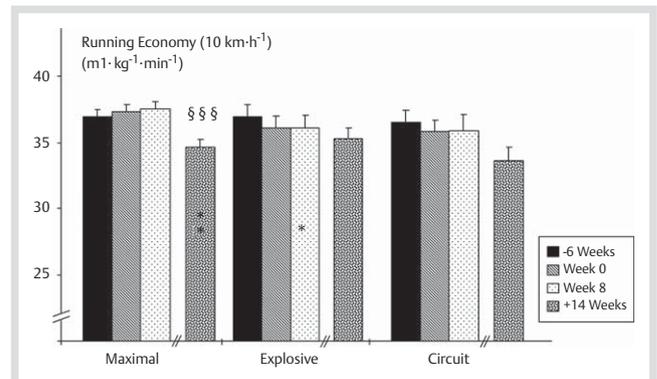
Basal levels of testosterone and cortisol (Table 4) did not change throughout the study. The ratio of testosterone/cortisol decreased significantly during reduced strength training in MAX ( $p < 0.05$ ) (Fig. 8).

**Discussion**

The primary findings of the present study demonstrated that maximal (MAX) and explosive (EXP) strength training groups improved strength, power, and maximal muscle activation systematically during both the preparatory period and the strength training intervention. Concomitantly, running velocity at  $VO_{2max}$ , ( $vVO_{2max}$ ) and running economy (RE) systematically and significantly improved in both MAX and EXP with only minor changes in  $VO_{2max}$ . The neuromuscular and strength changes associated with improvements in  $vVO_{2max}$  and RE seemed to be more important in augmenting endurance performance than increases in  $VO_{2max}$ . The circuit training control group (C) made smaller, but statistically significant improvements in strength and power over the preparatory strength training period and the strength training intervention. The changes in  $VO_{2max}$  and RE in C were not significant, however, the change in  $vVO_{2max}$  was significant. Despite the apparent detraining of strength that occurred with reduced strength training in MAX and EXP, the overall gains from strength training remained somewhat above pre-training values over the entire experimental period. This period, which also included an increase in endurance training volume and intensity, was associated with further improvements in  $vVO_{2max}$  and RE.



**Fig. 6** Velocity of running at  $VO_{2max}$  ( $vVO_2$ ) (mean  $\pm$  SE) measured at -6 weeks, weeks 0, 8 and +14. \* = significant difference from -6 weeks, + = significant difference from week 0 and § = significant difference from week 8 (\*, +, §,  $p < 0.05$ , \*\*, §§,  $p < 0.01$ , \*\*\* =  $p < 0.001$ ).

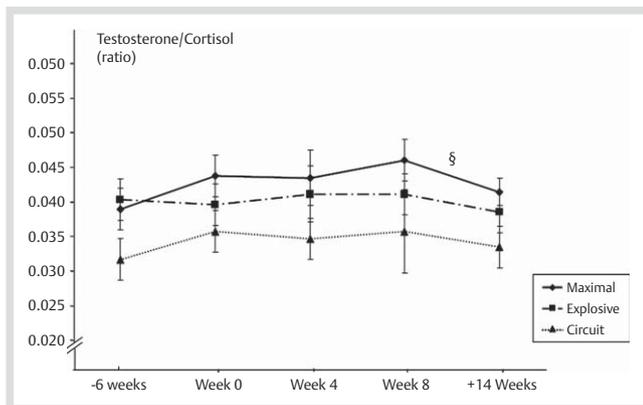


**Fig. 7** Running economy at  $10 \text{ km} \cdot \text{h}^{-1}$  over 28 weeks of training (mean  $\pm$  SE). \* = significant difference from -6 weeks and § = significant difference from week 8 (\* =  $p < 0.05$ , \*\* =  $p < 0.01$ , §§§ =  $p < 0.001$ ).

**Table 4** Basal levels of serum testosterone and cortisol (mean  $\pm$  SE) over 28 weeks of training.

		6-week preparatory strength training period		8-week strength training intervention			14-week reduced volume strength training period
		-6 weeks	week 0	week 4	week 8	+14 weeks	
<b>testosterone</b> (nmol/L)	maximal	17.0 $\pm$ 4.3 <sup>‡</sup>	18.7 $\pm$ 5.7	17.4 $\pm$ 5.4	17.7 $\pm$ 3.3	17.2 $\pm$ 3.5	
	explosive	15.7 $\pm$ 2.0	15.9 $\pm$ 3.7	17.1 $\pm$ 3.2	16.8 $\pm$ 3.0	16.3 $\pm$ 4.2	
	circuit	14.6 $\pm$ 4.7	15.5 $\pm$ 4.8	15.6 $\pm$ 2.6	13.7 $\pm$ 3.8	14.8 $\pm$ 4.8	
<b>cortisol</b> (nmol/L)	maximal	451.1 $\pm$ 65.0	440.4 $\pm$ 98.1	412.8 $\pm$ 79.9	401.9 $\pm$ 94.9	427.4 $\pm$ 79.1	
	explosive	414.8 $\pm$ 93.5	414.6 $\pm$ 78.9	452.5 $\pm$ 134.5	437.6 $\pm$ 120.2	442.3 $\pm$ 85.0	
	circuit	462.2 $\pm$ 77.7	435.5 $\pm$ 118.5	471.7 $\pm$ 108.4	427.0 $\pm$ 124.7	458.3 $\pm$ 117.6	

# = significant difference between week 4 and week 8, ‡ = significant difference between MAX and C, (\* =  $p < 0.05$ , \*\* =  $p < 0.01$ )



**Fig. 8** Ratio of serum testosterone to cortisol over 28 weeks of training. § = significant difference from week 8 ( $\xi = p < 0.05$ ).

The total improvement in 1RM was 8% in MAX over both strength training periods and 3% in EXP, but the difference between the groups was not significant. The increases in 1RM during the strength training intervention alone (week 0 to 8) were similar in both groups (~4%) despite the different strength training programs. A difference in the magnitude of improvement over these combined training periods was expected considering the progressively higher loads that MAX used for training (80–85% 1RM) versus the lighter loads (30–40% 1RM) used by EXP during the intervention; however, movement patterns may not have differed enough to distinctly show specificity of training [6]. The increases in strength that occurred in MAX and EXP, though significant, were not as great in magnitude as in studies examining only strength training in previously untrained individuals [1, 18]. The smaller magnitude of increase observed in our study may be related to differences in exercise protocols, in addition to concurrently performed endurance training. The plateau in strength gains that occurred in all groups following 10 weeks of training suggests that the strength training stimulus was either not adequate enough to induce additional changes, or it may indicate some interference of endurance training on strength development, an observation in line with e.g. Hickson [14] and Hunter et al. [16]. The significant 6% increase in 1RM load that C experienced following 10 weeks of training indicates that even low load/intensity strength training (using only body weight for 4 of those weeks) was sufficient to stimulate maximal strength improvements in individuals who have not previously used any type of resistance training.

Significant increases in muscle activation of VL and VM (an average of 18% and 34% in VL and VM, respectively) accompanied the improvements in strength over the entire strength training period in both MAX and EXP. Although caution should be exercised with regards to the present ultrasound method for measurement of muscle mass, our results indicated that in MAX, strength development may have also been influenced by a significant increase observed in muscle thickness of VL and VI. More drastic increases in muscle mass were not expected because training was not designed to be hypertrophic, and subjects were participating concurrently in endurance exercise.

Significant increases in CMJ jump height were observed in both strength training groups; however, changes in jumping height indicated that MAX made somewhat greater (n.s.) improvements (13%) in explosive strength over 10 weeks of strength training than EXP (11%). Although increases in jump height seem to be more systematic in MAX than in EXP, the overall sim-

ilarity in the increases in jumping height are attributed, in part, to 6 weeks of common training. Furthermore, this overall similarity indicates that movement patterns in the subsequent maximal and explosive strength training intervention programs may not have differed enough [6], or that the nature of CMJ testing might not show specificity of training. It has been suggested that specific explosive strength training adaptations may not occur unless a subject already has an “adequate” level of strength and power [32]. As a result, in recreationally trained endurance runners with no strength training background, maximal strength training may have had more of an effect on CMJ jump height than more specific explosive strength training. Subjects were also concurrently participating in endurance training activities, which have been reported to hinder specific adaptations to explosive resistance training [16, 22].

Following the period of reduced strength training volume and increased endurance training volume (and intensity), significant decreases were observed in maximal strength and muscle activation of the trained muscle groups (quadriceps femoris, VL) in MAX while maximal strength in EXP and C remained statistically unaltered. Decreases in maximal strength, muscle activation [19] and CMJ jump height are typically associated with reduced strength training volume [20]. Nevertheless, it is possible that these decreases were influenced by the progressive increase in endurance running volume (running kilometers per week) and intensity (training above aerobic and anaerobic thresholds) [14] (see Table 3) from the beginning of the study to the end of the study in all three groups. This significant increase in running kilometers coincided with plateaus/decreases in maximal strength, explosive strength and muscle activation. The increased endurance training (especially running) may have also resulted in greater mechanical stress that has previously been reported to interfere with muscle strength [4]. This finding is in agreement with e.g. Hickson [14] and Hunter et al. [16] who stated that early strength development may be hindered if aerobic training volume is high. Endurance running involves repeated low force production and impact loading which provides a different type of stimulus than that of strength training. Furthermore, leg muscles are not fully activated even during high-intensity running (on horizontal and up-hill), which indicates that there is a limitation to how many muscle fibers can be recruited to increase force production capabilities by running [6]. Thus, the 14-week period of reduced strength training and increased volume (and intensity) of endurance training appeared not to have provided a sufficient strength training stimulus to maintain increases in muscle activation and strength made during the preparatory period and strength training intervention.

The present study showed minimal increases in maximal oxygen uptake in all three training groups with a significant increase occurring only in MAX, and only over the preparatory period and strength training intervention. However, significant increases in  $v\dot{V}O_{2max}$  were continuously systematic over the preparatory period and strength training intervention in both MAX and EXP. In C, the increase was significant only between the beginning of the preparatory period and the end of the strength training intervention. Interestingly, the increase in  $v\dot{V}O_{2max}$  continued only in MAX and EXP over the period of reduced volume strength training and increased volume and intensity of endurance training. In addition, improvements in running economy (RE) were observed over the preparatory training period and the strength training intervention in EXP (at  $10 \text{ km} \cdot \text{h}^{-1}$ ) and in MAX over the entire 28 weeks of training (at  $10 \text{ km} \cdot \text{h}^{-1}$  and

12 km·h<sup>-1</sup>). Since increases observed in  $\text{VO}_{2\text{max}}$  were minimal, improvements that occurred in strength, power, and muscular activation likely contributed to improved  $\text{vVO}_{2\text{max}}$  and RE, and prepared subjects for increased endurance training volume. These observations are consistent with previous research by Daniels et al. [9] who observed that improvements in running performance are not necessarily related to increases in  $\text{VO}_{2\text{max}}$  alone. Furthermore, research by Paavolainen et al. [35,36] and Nummela et al. [33] attributes improved endurance performance to sport-specific economy and improved neuromuscular function. While endurance performance has typically been determined by measurement of maximal oxygen uptake ( $\text{VO}_{2\text{max}}$ ), fractional utilization of  $\text{VO}_{2\text{max}}$  and sport-specific economy, [3] these more recent studies have suggested that maximal anaerobic capacity and neuromuscular characteristics are additional predictors of endurance performance.

It should be noted that although the values of aerobic fitness measured at the beginning of this study were representative of recreational endurance athletes (non-elite), only minor changes in  $\text{VO}_{2\text{max}}$  were expected since the training intensity for much of the study was relatively low (below the aerobic threshold). Intermittent high-intensity training, such as interval training, is reported to be more effective than moderate intensity training in improving  $\text{VO}_{2\text{max}}$  [40]. On the other hand, changes in other endurance parameters such as  $\text{vVO}_2$  and RE may still be positively influenced by low intensity training [3]. Improvements in body composition, such as a decrease in mass or decreased %fat, such as those observed in all training groups in the present study may also positively influence endurance performance [10].

Serum concentrations of testosterone and cortisol remained statistically unaltered over the entire 28-week study in all three groups which indicated maintained homeostatic control. Over 10 weeks of strength training; however, the testosterone/cortisol ratio tended to increase concomitantly with concurrent strength and endurance training in MAX. Yet, following the reduced strength training and increased endurance training period, the serum ratio of testosterone/cortisol decreased significantly 10% in MAX, which indicates an increase in catabolic activity. Though significant, the decrease in serum testosterone/cortisol ratio was not below baseline; but it may have still contributed to strength and power decreases [23]. Suppressed resting concentrations of testosterone and elevated levels of cortisol have been reported to occur in typical male endurance athletes [8, 11]. Mode (strength versus endurance), intensity [41] and duration of training [41, 42] have been reported to influence these hormonal concentrations.

In conclusion, the findings of this study show that both maximal and explosive strength training performed concurrently with endurance training are more effective in improving strength, power and muscular activation in recreational endurance runners than concurrent circuit and endurance training. Improvements in strength, power, and muscle activation during the preparatory and strength training intervention periods appears to have contributed to enhanced endurance performance by improving  $\text{vVO}_{2\text{max}}$  and RE, and prepared subjects for increased endurance training volume which occurred during the final 14 week training period. Despite some detraining of strength that occurred during this period of reduced strength training and increased endurance training volume and intensity, overall strength and power improvements from strength training were maintained above pre-training values. Improvements in  $\text{vVO}_{2\text{max}}$

continued further in both MAX and EXP, while improvements in RE, continued further only in MAX. We conclude that maximal or explosive strength training performed concurrently with endurance training is more effective in improving strength and neuromuscular performance and in enhancing  $\text{vVO}_{2\text{MAX}}$  and RE in recreational endurance runners than concurrent circuit and endurance training.

#### Affiliations

<sup>1</sup> Department of Biology of Physical Activity, University of Jyväskylä, Finland

<sup>2</sup> KIHU, Research Institute for Olympic Sports, Jyväskylä, Finland

<sup>3</sup> UCT/MRC Research Unit for Exercise Science and Sports Medicine,

Department of Human Biology, University of Cape Town, South Africa

<sup>4</sup> Department of Kinesiology, University of Connecticut, Storrs, United States

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