Mixed Maximal and Explosive Strength Training in Recreational Endurance Runners

RITVA S. TAIPALE,1 JUSSI MIKKOLA,2 TIINA SALO,1 LAURA HOKKA,1 VILLE VESTERINEN,2 WILLIAM J. KRAEMER,3 ARI NUMMELA,2 AND KEIKO HÄKKINEN1

1Department of Biology of Physical Activity, University of Jyväskylä, Jyväskylä, Finland; 2KHIU - Research Institute for Olympic Sports, Jyväskylä, Finland; and 3Department of Kinesiology, University of Connecticut, Storrs, Connecticut

ABSTRACT

Taipale, RS, Mikkola, J, Salo, T, Hokka, L, Vesterinen, V, Kraemer, WJ, Nummela, A, and Häkkinen, K. Mixed maximal and explosive strength training in recreational endurance runners. J Strength Cond Res 28(3): 689–699, 2014—Supervised periodized mixed maximal and explosive strength training added to endurance training in recreational endurance runners was examined during an 8-week intervention preceded by an 8-week preparatory strength training period. Thirty-four subjects (21–45 years) were divided into experimental groups: men (M, n = 9), women (W, n = 9), and control groups: men (MC, n = 7), women (WC, n = 9). The experimental groups performed mixed maximal and explosive exercises, whereas control subjects performed circuit training with body weight. Endurance training included running at an intensity below lactate threshold. Strength, power, endurance performance characteristics, and hormones were monitored throughout the study. Significance was set at p ≤ 0.05. Increases were observed in both experimental groups that were more systematic than in the control groups in explosive strength (12 and 13% in men and women, respectively), muscle activation, maximal strength (6 and 13%), and peak running speed (14.9 ± 1.2 to 15.6 ± 1.2 and 12.9 ± 0.9 to 13.5 ± 0.8 km h⁻¹). The control groups showed significant improvements in maximal and explosive strength, but Speak increased only in MC. Submaximal running characteristics (blood lactate and heart rate) improved in all groups. Serum hormones fluctuated significantly in men (testosterone) and in women (thyroid stimulating hormone) but returned to baseline by the end of the study. Mixed strength training combined with endurance training may be more effective than circuit training in recreational endurance runners to benefit overall fitness that may be important for other adaptive processes and larger training loads associated with, e.g., marathon training.

KEY WORDS neuromuscular adaptations, recreational running, concurrent strength and endurance training, hormones, men and women, training

INTRODUCTION

Under certain conditions, when strength and endurance training are performed concurrently, adaptations may be compromised. This phenomenon is commonly referred to as the “interference effect” (13) and seems to be present when the volume and intensity of training are high and the duration of the training period is long (36). When an optimal concurrent training stimulus (volume, frequency, and intensity) is applied, however, the positive adaptations to concurrent strength and endurance training have been reported in high-level endurance athletes (14,22,26), as well as younger (18) and older (30) untrained or recreationally active men and women. In individuals with recreational or no training background, gains in endurance performance attributable to combined training have additionally been attributed to improvements in neuromuscular performance, e.g., increased voluntary muscle activation and strength and explosive strength development (30), which may also contribute to improvements in sport-specific economy (26,33).

The goal of endurance training (running) is to increase speed by means of, e.g., improved oxidative energy metabolism through increased capillary and mitochondrial density and increased enzyme activity (3). Significant improvements in neuromuscular performance by means of endurance running are not typically observed because running requires only repetitive low force production, which activates fewer motor units than heavy resistance exercise. Even intensive uphill running does not induce maximal activation of the leg muscles (31). Strength training, on the other hand, results in considerable improvements in strength of the trained muscle groups, regardless of age or gender, when the intensity and duration of the resistance training period are sufficient (14,18,22,26,30,36). Maximal strength training results in chronic neuromuscular adaptations, including muscle
hormonal responses to strength exercises typically include an acute increase in serum testosterone in men, which could also contribute to training-induced changes in basal levels for the hormone. In women, the acute response of testosterone is typically more subtle (16). The mode, intensity, and duration of a training session (34) influence hormonal concentrations and may influence the endocrine adaptations to training (20). Long-term hormonal adaptations to endurance training in both men and women have been characterized by a decrease, or no change, in the basal concentrations of hormones (8), whereas research has indicated that chronic hormonal adaptations in endurance athletes include depressed testosterone levels and increased levels of cortisol (CORT) (10), which indicate a catabolic state in the body that could negatively affect strength development and maintenance. Basal levels of thyroid stimulating hormone (TSH) have previously been reported to be unaffected by prolonged strength training (27); however, very intensive short-term (1 week) strength training has been shown to decrease the levels of TSH (28) and a link between lower TSH and stress has been reported (23). Hormonal responses to combined strength and endurance training seem to differ from responses to "pure" training, e.g., CORT levels increased more during high-volume combined strength and endurance training when compared with individuals performing strength training alone (19). A prolonged catabolic state and additional stress are typically undesirable for maintaining fitness and health, thus monitoring hormones may be important for optimizing training programs even in recreational athletes.

**Methods**

**Experimental Approach to the Problem**

We previously (33) examined the effects of periodized maximal vs. explosive strength training, combined with endurance training, on neuromuscular adaptations and changes in endurance performance in male recreationally trained endurance runners. Both modes of strength training, when performed concurrently with a low volume and intensity of endurance training, improved strength and neuromuscular performance while also positively influencing peak running speed ($S_{peak}$) and running economy (RE). Circuit training with body weight only as a load combined with endurance training was not as effective as maximal or explosive strength training in inducing improvements. Mixed maximal and explosive strength training may be a more potent stimulus for producing explosive power than maximal or explosive strength training alone (21). Although strength and power are generally desired by recreational athletes, they typically have limited time at the gym, especially, if they are full-time workers. Thus, the purpose of this study was to examine the effects of low-volume periodized mixed (maximal and explosive) strength training added to a low volume and intensity of endurance training in both male and female recreational endurance runners before starting a marathon training program. The planned training meets the minimum guidelines for exercise prescription as outlined by the American College of Sports Medicine (9). The aim of the study was to evaluate neuromuscular, cardiorespiratory, and hormonal training adaptations to this low-volume periodized mixed (maximal and explosive) strength training added to a low volume and intensity of endurance training. We hypothesized that mixed maximal and explosive strength training would be more effective than circuit training with only body weight as a load in improving neuromuscular characteristics and expect that this will have a positive, albeit small, influence on the endurance performance characteristics in individuals who already participate recreationally in endurance running. Significant changes in the basal concentrations of serum hormones were not expected because of the low volume and intensity of the combined training.

**Subjects**

Thirty-four subjects (aged 21–45 years; 16 men and 18 women) with a low-volume recreational endurance running background were recruited to participate in this study as part of a marathon training school program in which these recreationally active subjects were seeking guidance on endurance and strength training programs that may be used to prepare them to train for a half or full marathon. Subjects were divided into 4 groups matched for age, anthropometrics, training experience, strength, $V_{O_{2}}$max, $S_{peak}$, running speed at lactate threshold ($S_{LT}$), and speed at respiratory compensation threshold ($S_{RCP}$) after baseline testing at week 0 (Table 1). Endurance training was planned as preparatory conditioning for marathon or half-marathon training that subjects took part in after the completion of this study. Subjects received written and oral information about the study design and measurement procedures. The possible risks and benefits of partaking in the study were explained to the subjects before signing an informed consent document and screening by a physician. The subjects in this study were not using medications and did not have any injuries that would affect their physical performance or the results of this study. Subjects were asked to continue their normal daily physical activity, such as biking or walking to work, for the duration of the study. All female subjects were premenopausal. Ethical approval was granted by the University Ethical Committee and the study was conducted according to the provisions of the most recent Declaration of Helsinki and upholds published ethical standards in sport and exercise science research (11).

**Study Design and Planning**

All groups performed endurance and strength training concurrently for the entire experimental period. Strength training in the experimental groups consisted of a mixture of maximal and explosive exercises described in further detail below, whereas the control groups of men and women performed circuit training using only their body weight as a load. One subject was excluded from the results of the control group of men because of low training compliance.
Strength training throughout the 16-week study in both the experimental and control groups was focused on the knee extensors because they are a major muscle group at work in running and daily human locomotion. All strength training sessions in the experimental and control groups were preceded by a low-intensity aerobic warm-up of ~20 minutes. The 16-week study was divided into two 8-week periods. A preparatory strength training period of 8 weeks was completed first to familiarize subjects with equipment and proper lifting techniques and to ensure that subjects had a similar background in training before starting the experimental training. The preparatory strength training period consisted of 8 weeks of training (12 sessions) with compliance of an average of 1.2 ± 0.5 strength training sessions per week. During this period, all subjects were trained using exercises similar to those used in the experimental groups during the strength training intervention (Table 2).

Loads during this 8-week preparatory strength training period progressed from 50 to 70% (1 repetition maximum [1RM]). These loads were used for subjects to learn proper technique and to minimize the effect of learning during the actual strength training intervention. After the preparatory period, the experimental groups began their specified combined maximal and explosive strength training (Table 2) and the control groups began circuit training with only body weight as a load for a period of 8 weeks. Exercises for this group included squats, push-ups, lunges, sit-ups, calf-raises, back extensions, planks, and step-ups. A work to rest ratio of 45 seconds:15 seconds and 50 seconds:10 seconds was used during weeks 8–12 and 12–16, respectively. Strength training frequency during the first 4 weeks of the strength training intervention was an average of 1.75 ± 0.5 sessions per week, whereas during the second 4 weeks of the strength training intervention, the frequency slightly decreased to an average of 1.25 ± 0.5 sessions per week. (All members of the experimental group completed 12–14 of the 14 planned training sessions training sessions.) No statistically significant differences in training frequency were observed between training groups (p > 0.05). All strength training sessions were supervised by experienced members of the research group.

Subjects in both the experimental and control groups concurrently performed endurance training with an average frequency of 3 ± 0.75 sessions per week during the 8-week preparatory period. Training frequency decreased slightly during the strength intervention to an average of 2.75 ± 0.5 sessions per week. During the preparatory training period and strength intervention, endurance training in all groups was performed below lactate threshold (LT). Endurance training volume during the preparatory strength period and strength intervention was relatively constant in terms of both running kilometers and total endurance training time (subjects also participated in a low volume of other endurance activities like biking and skiing, typical endurance activities in Finland, Table 2). Training volume, in terms of time and kilometer, increased gradually (not specified) from the preparatory strength period into the actual 8-week strength intervention as part of the planned progressive combined training program. There were no group differences in training volume (time or kilometer) in these 2 periods. Endurance training plans were personalized and adjusted after each aerobic testing session (weeks 0 and 8). All endurance training sessions were monitored continuously using a heart rate (HR) monitor (Suunto t6, Vantaa, Finland). Subjects kept a detailed training diary and reported back to the laboratory at regular intervals to upload training data from the HR monitor. Strength measurements took place before the preparatory strength period (week 0), before, in the middle, and after the strength intervention (weeks 8, 12, and 16).

### Measurements

**Body Composition**

In addition to standing height, 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 0730 and 0800 AM. Subjects always arrived for testing in a fasted state, which helped to keep the possible confounding variables of diet and hydration status to a minimum. Subjects were instructed to remove excess clothing, watches, shoes, and socks before the measurement.

**Serum Hormones.** For the examination of basal serum hormones, venous blood samples (10 ml) were collected at weeks 0, 8, 12, and 16 using sterile needles into serum tubes (Venosafe; Terumo Medical Co., Leuven, Belgium) by a qualified laboratory technician. Subjects were tested after 12 hours of fasting between 0730 and 0800 hours. Whole blood was centrifuged at 2500g (Megafuge 1.0R; Heraeus, Langenfeld, Germany) for 10 minutes after which serum was removed and stored at 280°F until analysis. Samples were used for the determination of serum testosterone, 

### Table 1. Subject characteristics (mean ± SD).*

<table>
<thead>
<tr>
<th></th>
<th>Age (y)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>VO2max (ml·kg⁻¹·min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M <em>(n = 9)</em></td>
<td>31 ± 9</td>
<td>178 ± 5</td>
<td>78 ± 7</td>
<td>50 ± 5</td>
</tr>
<tr>
<td>MC <em>(n = 7)</em></td>
<td>34 ± 9</td>
<td>180 ± 5</td>
<td>84 ± 11</td>
<td>46 ± 6</td>
</tr>
<tr>
<td>W <em>(n = 9)</em></td>
<td>29 ± 7</td>
<td>168 ± 5</td>
<td>62 ± 6</td>
<td>45 ± 4</td>
</tr>
<tr>
<td>WC <em>(n = 9)</em></td>
<td>35 ± 6</td>
<td>165 ± 7</td>
<td>60 ± 7</td>
<td>43 ± 6</td>
</tr>
</tbody>
</table>

*M = experimental men; MC = control men; W = experimental women; WC = control women.
CORT, and TSH. Analyses were performed using chemical luminescence techniques (Immunlite 1000; DCP Diagnostics Corporation, Los Angeles, CA, USA) and hormone-specific immunoassay kits (Siemens, New York, NY, USA). The sensitivity of testosterone, CORT, and TSH assays were 0.7 nmol/L, 5.5 nmol/L, and 0.004 mIU/L, respectively.

The intra-assay coefficients of variation for testosterone, CORT, and TSH were 5.7, 4.6, and 3.9%, respectively.

PERFORMANCE MEASURES

Aerobic Capacity

Endurance capacity was measured by maximal oxygen uptake (V\textsubscript{O\textsubscript{2}}\text{max}) using a treadmill running protocol (22). The running velocity began at 7 km·hour\textsuperscript{-1} for women and 8 km·hour\textsuperscript{-1} for men and was increased by 1 km·hour\textsuperscript{-1} at the end of every third minute until volitional exhaustion, a plateau in V\textsubscript{O\textsubscript{2}}\text{max} and respiratory exchange ratio above 1.1. Treadmill incline remained a constant 0.5\% throughout the test. Heart rate was recorded continuously using a HR monitor (Suunto t6). Mean HR values from the last minute of each stage were used for the analysis. Oxygen consumption was measured breath-by-breath throughout the test using a portable gas analyser (Oxycon Mobile; Jaeger, Hoechberg, Germany) that was calibrated using known gas concentrations according to manufacturer instructions before each test. V\textsubscript{O\textsubscript{2}}\text{max} was accepted as the highest average 60 seconds V\textsubscript{O\textsubscript{2}} value. Fingertip blood samples were taken every third minute to measure lactate concentrations. For blood sampling, the treadmill was stopped for approximately 15–20 seconds. Blood lactates (Blas) were analyzed using a Biosen S-Line Lab+ lactate analyzer (EKF Diagnostic, Magdeburg, Germany). Lactate threshold and respiratory compensation threshold (RCT) were determined using Bla, ventilation, V\textsubscript{O\textsubscript{2}}, and V\textsubscript{CO\textsubscript{2}} (production of carbon dioxide) (2). Peak running speed (S\textsubscript{peak}) was calculated as follows:

$$S_{\text{peak}} = \frac{\text{speed of the last whole completed stage (km·h}^{-1}) + \text{(running time (s) at exhaustion – 30 seconds)}}{180-30 \text{ seconds)) × 1 \text{ km·h}^{-1}}.$$
Maximal and Explosive Strength Measurements

The 1 Repetition Maximum. The 1RM of the lower extremities (maximal dynamic bilateral horizontal leg press in a seated position) was measured using a David 210 dynamometer (David Sports Ltd., Helsinki, Finland) (16). Before 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 minute of rest between sets. After this warm-up, no more than 5 attempts to reach 1RM were made. Leg press repetitions 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 participant 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 (CMJ) height (7). Subjects were instructed to stand on the force platform with their feet approximately hip-width apart with their hands on their hips through the entire movement. Subjects performed a quick and explosive CMJ on verbal command so that knee angle for the jump was no less than 90°. Force data were collected and analyzed by computer software (Signal 2.14; CED, Cambridge, United Kingdom), which used the equation $h = \frac{I^2}{2mg}$ to calculate jump height from impulse, where $I$ is the impulse, $g$ is the gravity, and $m$ is the mass of participant.

Electromyographic Activity. Electromyographic (EMG) activity was recorded from the vastus lateralis (VL) and vastus medialis (VM) of the right leg during 1RM and CMJ at a sampling frequency of 2,000 Hz, and then filtered (20 Hz low pass filter for force and 20–350 Hz band pass filter for EMG signals after amplification at gain of 500 and sampling bandwidth of 10–500 Hz). Electrode positions were marked with small ink tattoos (17) 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 (32) were followed for skin preparation, electrode placement, and orientation. Interelectrode 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 (Telememo 2400R; Noraxon, Scottsdale, AZ, USA) from which the signal was relayed to the computer via an AD converter (Micro1401; CED). Analysis of 1RM and CMJ EMG was performed using customized scripts (Signal 4.04; CED) and filtered using a band pass of 20–350 Hz before analysis. In 1RM, whole range EMG was recorded from the starting knee angle approximately 65° to full leg extension of 180°, whereas in CMJ EMG was examined during the concentric phase of the movement as determined by the force signal (knee angle of approximately 90° to full leg extension of 180°).

Figure 1. Maximal strength (mean ± SD) in terms of maximal bilateral dynamic leg press load (1RM load) and percent change during the entire experimental period. * indicates $p < 0.05$, **$p < 0.01$, ***$p < 0.001$ from week 0 and + indicates $p < 0.05$, +++$p < 0.001$ from week 8. Significant group differences are indicated by a line and * ($p < 0.05$); M = experimental men; MC = control men; W = experimental women; and WC = control women.
Maximum root mean square EMG from the concentric phase of each movement was analyzed by a customized script (Signal 4.04; CED) and was used in further analysis.

**Statistical Analyses.** Standard statistical methods were used for the calculation of means, SD, and Pearson product-moment correlation coefficients. Between group differences and within group differences for all variables were analyzed using a repeated measures factorial analysis of variance (time × sex × group). In the presence of a significant F-value, post hoc comparison of means was provided by Fisher’s least significant difference test. The criterion for significance was set at *p = 0.05, **p < 0.01, and ***p < 0.001. Statistical analysis was completed with SPSSWIN 15.0 (SPSS, Inc., Chicago, IL, USA).

**RESULTS**

Increases in maximal strength were systematically progressive and significant in both experimental groups (M and W) over the entire experimental period (Figure 1). During the preparatory strength training period, maximal strength (1RM) increased significantly in both M and W (3%, p ≤ 0.05 and 7%, p < 0.001, respectively) and further improved after the first 4 weeks of the strength training intervention between weeks 8 and 12 (3%, p ≤ 0.05 and 7%, p < 0.001 in M and W, respectively). Some significant improvements were observed in both control groups, including a significant increase in maximal strength of MC and WC from weeks 0–12 (6% and 7%, p ≤ 0.05); however, no further improvements were observed after week 12. Improvements in maximal strength plateaued in all of the groups after a total of 12 weeks of training.

A significant difference in relative strength development over the entire experimental period (week 0–16) was
observed between the experimental group of men and women \((p \leq 0.05)\) and between the experimental group of women and the women’s control group \((p \leq 0.05)\) (Figure 1). No systematic changes were observed in EMG recorded during IRM in any of the groups.

Improvements in CMJ height were progressive and significant in both experimental groups (Figure 2). In M, significant improvements were observed after the 8-week preparatory period \((5\%, p < 0.01)\), whereas continued significant improvements were observed between weeks 8 and 16 \((6\%, p < 0.001)\) and in the final 4 weeks of training (between weeks 12 and 16: \(5\%, p \leq 0.05\)). In W, significant improvements in jumping height were observed between weeks 0 and 12 (from week 0: \(11\%, p < 0.001\) and from week 8: \(7\%, p < 0.01\) after which a plateau in jump height was observed. Some significant improvements in CMJ height were observed in the control groups. In MC, the significant improvement \((9\%, p < 0.001)\) in jumping height plateaued already after the preparatory period, whereas WC made significant improvements in jumping height only after completing the 8-week preparatory period and the first 4 weeks of the training intervention \((7\%, p \leq 0.05)\). Significant improvements in muscle activation (EMG) of VL and VM during CMJ coincided with improvements in CMJ height in M \((p \leq 0.05\) from weeks 0 to 8) and W \((p < 0.001\) from weeks 0 to 16) (Figure 2).

In both groups of men, there was a significant correlation between strength development (IRM) and explosive strength development (CMJ height) between week 0 and week 12 \((r = 0.54, p \leq 0.05)\), whereas the respective correlation approached significance in women during the strength training intervention (between weeks 8 and 16, \(r = 0.48, p = 0.052\)).

Peak running speed increased in all groups after preparatory training \((p < 0.01)\). Further improvements were observed in M, MC, and W after the training intervention \((p < 0.01, p < 0.001,\) and \(p \leq 0.05,\) respectively) (Figure 3).

In terms of \(V_{O2\text{max}}\), only MC and W showed any significant improvement during the 16-week experimental period. Control men improved \(V_{O2\text{max}}\) in ml\(\cdot\)kg\(^{-1}\)\(\cdot\)min\(^{-1}\) between weeks 0 and 8 \((45.7 \pm 3.0\) to \(47.0 \pm 6.2, p < 0.01)\) and between weeks 8 and 16 \((47.0 \pm 6.2\) to \(49.8 \pm 7.0, p < 0.01)\). In W, a significant improvement was observed in \(V_{O2\text{max}}\) in ml\(\cdot\)kg\(^{-1}\)\(\cdot\)min\(^{-1}\) between weeks 8 and 16 \((43.7 \pm 2.4\) to \(46.0 \pm 2.8, p < 0.01)\).
Mixed Maximal and Explosive Strength Training in Recreational Endurance Runners

<table>
<thead>
<tr>
<th>Table 3. Serum hormone concentrations (mean ± SD).*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Week 0</td>
</tr>
<tr>
<td>TESTO (nmol·L⁻¹)</td>
</tr>
<tr>
<td>M</td>
</tr>
<tr>
<td>MC</td>
</tr>
<tr>
<td>W</td>
</tr>
<tr>
<td>WC</td>
</tr>
<tr>
<td>CORT (nmol·L⁻¹)</td>
</tr>
<tr>
<td>M</td>
</tr>
<tr>
<td>MC</td>
</tr>
<tr>
<td>W</td>
</tr>
<tr>
<td>WC</td>
</tr>
<tr>
<td>TSH (μU·ml⁻¹)</td>
</tr>
<tr>
<td>M</td>
</tr>
<tr>
<td>MC</td>
</tr>
<tr>
<td>W</td>
</tr>
<tr>
<td>WC</td>
</tr>
</tbody>
</table>

*M = experimental men; MC = control men; W = experimental women; WC = control women; TESTO = testosterone; CORT = cortisol; TSH = thyroid stimulating hormone.
†From week 0.
‡From week 8.
§From week 12.

45.4 ± 2.7, p ≤ 0.05). No statistically significant changes were observed in M or WC (50.9 ± 5.4 to 51.7 ± 5.4 and 42.8 ± 5.9 to 44.8 ± 6.4 between weeks 0 and 16, respectively).

Both groups of men (M and MC) showed significant improvements in economy and decreased Bla concentration during the submaximal loads of \( \bar{V}O_2 \) max testing (Figure 4). In M, HR decreased at submaximal speeds from 9 to 13 km·h⁻¹ (p < 0.01–0.001) and in MC, from 8 to 13 km·h⁻¹ (p < 0.01–0.001). Submaximal Bla decreased in M at submaximal speed from 8 to 11 km·h⁻¹ (p ≤ 0.05–0.01) and in MC, from 8 to 13 km·h⁻¹ (p < 0.01–0.001). In women (W and WC), significant changes were primarily observed in decreased Bla concentration. In W, HR decreased at submaximal speeds of 9 and 10 km·h⁻¹ (p ≤ 0.05) and in WC at 10 km·h⁻¹ (p ≤ 0.05). Blood lactate decreased in W at submaximal speeds of 8–12 km·h⁻¹ (p ≤ 0.05–0.001), whereas in WC, Bla decreased significantly at only 8, 19, and 11 km·h⁻¹ (p ≤ 0.05–0.001). There were no significant changes in RCT speed in any of the groups.

A significant increase in serum testosterone concentration in M was observed between weeks 0 and 12 (p ≤ 0.05) followed by a significant return to baseline between weeks 12 and 16 (p < 0.01) (Table 3). A significant decrease in TSH was observed in both groups of women (between weeks 8 and 12 in W, p < 0.01 and weeks 0 and 8 in WC, p < 0.01). Serum concentrations of CORT remained statistically unaltered (Table 3).

**Discussion**

Mixed maximal and explosive strength training performed concurrently with endurance training increased explosive strength (CMJ), muscle activation (EMG of CMJ), and maximal strength (1RM) in the experimental groups of men and women while also improving the peak running speed (\( S_{\text{peak}} \)). Increases were more progressive and larger than those of the circuit training groups, but not statistically so. Significant increases in explosive and maximal strength were observed in both groups of women (between weeks 8 and 12), whereas in W and WC, changes were smaller and less systematic (not specified) than those achieved in the experimental groups. Circuit training did not significantly alter muscle activation and improvements in \( S_{\text{peak}} \) increased only in the control group of men. The observed increases in explosive strength, associated improvements in rapid muscle activation, and gains in maximal strength resulting from mixed strength training, combined with present low volume and intensity endurance training likely influenced improvements in submaximal running characteristics (Bla and HR) and RE in both M and W. Interestingly, both groups of men showed more systematic positive changes in terms of submaximal running characteristics than women, whereas \( \bar{V}O_2 \) max improved significantly only in MC and W. Overall, the low volume of mixed maximal and explosive strength training combined with endurance training showed greater benefits to improve neuromuscular capabilities than circuit training with body weight alone combined with endurance training. Because endurance training may blunt strength training adaptations, a more potent stimulus of strength training, although performed with a low frequency seemed to be slightly more advantageous for improving overall fitness than body weight circuit training.

Increases in CMJ during the 16-week study in the experimental groups of men (12%) and women (13%) were larger and more progressive (not specified) and systematic than those of the control groups and were accompanied by
increases in muscle EMG during the entire study period. The preparatory period induced significant gains in CMJ height in M and MC, but only the mixed maximal and explosive strength training that occurred during 8-week strength training intervention was able to induce further improvements in men. It also seemed that the experimental groups of men and women had differences in their time course of adaptations to the experimental mixed strength training combined with endurance training. Countermovement jump height in men improved progressively at each measurement point, whereas improvements in women were not observed until 12 weeks of training, after which an immediate plateau in improvements was observed. Furthermore, experimental men and women showed differences in the time course of changes in CMJ muscle activation. Muscle activation increased significantly between weeks 0 and 8; however, subsequent measurements showed fluctuations in adaptations, which suggested that the strength training stimulus was inadequate to produce and maintain adaptations in the muscle activation. Similar improvements in explosive performance and muscle activation have been observed after explosive-type strength training combined with endurance training (22,25,33). The adaptations that occurred in these studies may be attributed to a higher firing frequency and increased motor unit recruitment (35), which is also likely in this study. The mixed strength training stimulus during the final 4 weeks of the 8-week intervention included a decrease in the volume of maximal strength training and an increase in the volume of explosive strength training. Along with slight increase in running volume in the final 4 weeks of training, this slight change in strength training stimulus may have contributed to continued gains in the neural component of power in explosive strength performance. These adaptations are in-line with the effects of mode specificity of training (6).

Increases in 1RM in the experimental groups of men and women during the entire study period (6% and 13% for M and W) were also more progressive and systematic than those in the controls (3% and 6% for MC and WC, significant difference between W and WC $p \leq 0.05$). The significant difference in strength development between experimental men and women may be expected because men are generally stronger and may have less potential for increases in strength than women. It should be noted that both groups of men and women have potential for making gains in strength as neither have previously participated in strength training (1,15). Nevertheless, the difference in strength development between the experimental and control groups of women is attributed to the use of loads and explosive training vs. body weight only. Adaptations in 1RM muscle activation in this study were not observed, which may be a result of using slightly different movement patterns between the testing and training procedures, or may indicate that insignificant neural adaptations during maximal strength performance were elicited by the present low frequency mixed maximal and explosive training. Increases in 1RM of the control groups were expected because even circuit training with only body weight as a load is likely to cause some improvements in strength in individuals with no background in strength training. Maximal strength may, however, fluctuate as much as 5% on a daily basis (29); thus, the increases in 1RM in the men’s control group may be more attributable to daily variation rather than actual gains in strength.

Strength training with heavy loads alone typically leads to larger strength increases than those that occurred in this study (1). The smaller magnitude of increases in strength in our experimental groups and plateau in the final weeks of training may be because of the present mixed strength training stimulus, or the low frequency of training, or could be a result of concurrently performing endurance training (4,13). In addition, the observed plateau in strength gains that occurred during the final 4 weeks of the intervention most likely indicates that there was not an adequate strength training stimulus in terms of either volume or intensity or both.

Previous research (24,26) indicates that improved endurance performance is related to improved neuromuscular function and sport-specific economy. Furthermore, neuromuscular characteristics might be a predictor of endurance performance in addition to maximal oxygen uptake, which may otherwise be relatively homogeneous as in the study by Paavolainen et al. (26). Thus, it is important to note that the peak running speed progressively improved in the experimental groups of men and women and in the control group of men. Interestingly, the control group of women was the only group to show a plateau in $S_{peak}$ development suggesting that circuit training combined with endurance running did not provide an adequately enough training stimulus to increase their running velocity. Peak running speed is an important value in terms of evaluating endurance performance as it blends $V_o$max and RE into a single value that can help to determine aerobic differences between runners (5).

The aerobic fitness values of our subjects were the representative of recreational endurance athletes. Significant changes in $V_o$max were not expected because the endurance training intensity during the entire 16-week study was intentionally low (primarily below RCT). Intermittent high-intensity training, such as interval training, is reported to be significantly more effective than moderate intensity training in improving $V_o$max (12); however, it is worth noting that changes in other endurance parameters such as $S_{peak}$, RE, and other submaximal running characteristics such as HR and Bla may be positively influenced by low-intensity endurance training (3) such as that used in our study.

Significant changes in the basal serum hormone concentrations were not expected because of the relatively low volume and intensity of training, as the subjects were only recreationally trained; addition of a new training stimulus may be expected to cause some small perturbations in hormonal homeostasis. The significant increase in the basal serum testosterone concentration in the experimental group of men during the initial 12 weeks of strength training...
Mixed Maximal and Explosive Strength Training in Recreational Endurance Runners

indicates the development of a more anabolic environment in the body, whereas the subsequent significant drop in testosterone during the last 4 weeks of training may be associated with the decrease in maximal strength training stimulus or could be indicative of increased overall training stress of combined training. Nevertheless, serum CORT values remained statistically unaltered and the serum testosterone value did not drop below baseline indicating that a catabolic state was not achieved. A significant decrease occurred in TSH levels of the experimental group of women after the first 12 weeks of combined strength and endurance training. In the control women, the decrease in TSH was significant only after the initial 8-week preparatory training period when strength training with weights was used in this group. Thyroid function is under strict homeostatic control, so large fluctuations in TSH were not expected (19). Nevertheless, previous studies have also shown that the basal levels of TSH may decrease after short-duration intensive strength training (28) or remain the same after prolonged strength training (27). It may be hypothesized that decreased TSH in the women in our study reflects stress (23), which may be because of added strength training as the decrease was apparent in both W and WC after 8 weeks of concurrent strength and endurance training. It is unclear as to how significant these fluctuations might be because TSH values stayed within normal physiological ranges and fluctuations in CORT did not reflect additional stress. It is also important to note that serum concentrations of testosterone, CORT, and TSH had all returned to baseline by the end of the experimental period (8 weeks + 8 weeks) indicating that subjects had adjusted to training.

In conclusion, improvements in explosive strength and muscle activation, as well as maximal strength seemed to have, in combination with low volume and intensity endurance training, contributed to enhanced endurance performance by improving $\text{S}_{\text{peak}}$ and submaximal running characteristics, such as HR and Bla. Men seemed to have made more systematic improvements than women in terms of improving submaximal running characteristics despite women making more significant gains in maximal strength. The significant increase in serum testosterone in the experimental group of men suggests that the initial weeks of training stimulated an anabolic environment in the body, whereas the subsequent decrease in testosterone during the final weeks of training may indicate increased stress as the volume and intensity of combined training progressively increased for the study period. In both groups of women, the significant decrease in TSH with the onset of strength training may also be indicative of increased physical stress. In practice, a low frequency of mixed maximal and explosive strength training combined with endurance training can be used in male and female recreational endurance athletes to promote development in maximal and explosive strength and selected characteristics of endurance performance for a short training period.

**Practical Applications**

Periodized mixed maximal and explosive strength training approximately twice a week combined with a relatively low volume of endurance training (running) can be used in male and female recreational endurance athletes to promote development in maximal and explosive strength as well as selected characteristics of endurance performance and to benefit overall fitness within a relatively short time course. Greater improvements in neuromuscular performance can be achieved using mixed maximal and explosive strength training for conditioning than circuit training with body weight only that may be important for other adaptive processes and larger training loads associated with, e.g., half or full marathon training (33).

**Acknowledgments**

This study was a cooperative effort between KIHU - Research Institute for Olympic Sport and the Department of Biology of Physical Activity at the University of Jyväskylä. Funding was provided by the Finnish Funding Agency for Technology and Innovation (TEKES), KIHU - Research Institute for Olympic Sport, the Department of Biology of Physical Activity, and the Foundation of Sports. The authors wish to thank the technical staff at KIHU - Research Institute for Olympic Sport (Esa Hynynen and Sirpa Vänttinen) and the Department of Biology of Physical Activity, University of Jyväskylä’s technical staffs (Pirkko Puttonen, Risto Puurtinen, Sirpa Roivas, and Markku Ruuskanen). None of the authors declare any conflicts of interest and the results of this study do not constitute endorsement by the authors or the National Strength and Conditioning Association.

**References**


