Effects of a Concurrent Strength and Endurance Training on Running Performance and Running Economy in Recreational Marathon Runners

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Abstract

Ferrauti, A., Bergermann, M., and Fernandez-Fernandez, J. Effects of a concurrent strength and endurance training on running performance and running economy in recreational marathon runners. J Strength Cond Res 24(10): 2770–2778, 2010—The purpose of this study was to investigate the effects of a concurrent strength and endurance training program on running performance and running economy of middle-aged runners during their marathon preparation. Twenty-two (8 women and 14 men) recreational runners (mean ± SD: age 40.0 ± 11.7 years; body mass index 22.6 ± 2.1 kg m⁻²) were separated into 2 groups (n = 11; combined endurance running and strength training program [ES]: 9 men, 2 women and endurance running [E]: 7 men, and 4 women). Both completed an 8-week intervention period that consisted of either endurance training (E: 276 ± 108 minute running per week) or a combined endurance and strength training program (ES: 240 ± 121-minute running plus 2 strength training sessions per week [120 minutes]). Strength training was focused on trunk (strength endurance program) and leg muscles (high-intensity program). Before and after the intervention, subjects completed an incremental treadmill run and maximal isometric strength tests. The initial values for VO₂peak (ES: 52.0 ± 6.1 vs. E: 51.1 ± 7.5 ml·kg⁻¹·min⁻¹) and anaerobic threshold (ES: 3.5 ± 0.4 vs. E: 3.4 ± 0.5 m·s⁻¹) were identical in both groups. A significant time × intervention effect was found for maximal isometric force of knee extension (ES: from 4.6 ± 1.4 to 6.2 ± 1.0 N·kg⁻¹, p < 0.01), whereas no changes in body mass occurred. No significant differences between the groups and no significant interaction (time × intervention) were found for VO₂ (absolute and relative to VO₂peak) at defined marathon running velocities (2.4 and 2.8 m·s⁻¹) and submaximal blood lactate thresholds (2.0, 3.0, and 4.0 mmol·L⁻¹). Stride length and stride frequency also remained unchanged. The results suggest no benefits of an 8-week concurrent strength training for running economy and coordination of recreational marathon runners despite a clear improvement in leg strength, maybe because of an insufficient sample size or a short intervention period.

Key Words: intensity strength training, concurrent training

Introduction

Running economy has been defined as oxygen uptake required at a given submaximal velocity (9,20,28) and should be viewed relative to one’s maximum oxygen uptake (VO₂max) (11). Besides anthropometric preconditions (24) (e.g., body weight and body composition, length and composition of the lower extremities, upper and lower body size relation), several movement criteria are supposed to establish an economic running technique model. These criteria are brief ground contacts, small knee angles in the contact, and swing phases, distinctive hip extension at toe-off, and a small vertical oscillation of the center of gravity. Furthermore, small vertical force peaks at foot strike and high elastic energy storage seem to play an important role in this model (2,28,33,39). Intervention studies aimed at an optimization of running economy are usually focused on an improvement of running coordination (1,23) or on an increase in muscle work efficiency by different kinds of strength training (18,29,31).

Coordinative training interventions (e.g., running technique exercises) often failed to influence running mechanics and running economy (1,23). It has been shown that running economy was impaired when runners diverge from their usual technique (e.g., by varying stride length) (9). Probably, the energetic demand of running adapts to the individual running technique and the respective running economy seems to underlie a process of self-optimization (33).

Strength training on the other hand is currently supposed to increase muscle work efficiency and to improve trunk movement criteria are supposed to establish an economic running technique model. These criteria are brief ground contacts, small knee angles in the contact, and swing phases, distinctive hip extension at toe-off, and a small vertical oscillation of the center of gravity. Furthermore, small vertical force peaks at foot strike and high elastic energy storage seem to play an important role in this model (2,28,33,39). Intervention studies aimed at an optimization of running economy are usually focused on an improvement of running coordination (1,23) or on an increase in muscle work efficiency by different kinds of strength training (18,29,31).

Coordinative training interventions (e.g., running technique exercises) often failed to influence running mechanics and running economy (1,23). It has been shown that running economy was impaired when runners diverge from their usual technique (e.g., by varying stride length) (9). Probably, the energetic demand of running adapts to the individual running technique and the respective running economy seems to underlie a process of self-optimization (33).

Strength training on the other hand is currently supposed to increase muscle work efficiency and to improve trunk
stability, which allows for a higher training volume and a better impulse transmission (8). In detail, strength training may very positively influence many parameters that are supposed to be correlated with running economy. Some of the most important are the ground reaction forces, an active hip extension at toe-off, and a high force development during a short ground contact, all leading to an increase in energy transfer and stride length (20).

In elite running, the majority of strength training intervention studies showed positive effects on running economy and running performance. For the leg muscles, a training of motor unit recruitment patterns, usually performed with high intensities (90–100% of 1 repetition maximum [1RM]) and low volume (1–3 repetitions), seems to be applicable, because it is supposed to have less hypertrophic and weight gaining effect and to improve the eccentric–concentric transition including an effective stretch–shortening cycle (13,14,30, 34,35). Similar positive effects on running performance have been shown when emphasizing plyometric or explosive exercises (15,29,31). In addition, there is an increase in the recognition of the core musculature as critical for the transfer of energy from the larger torso to the smaller extremities, which may be more involved in the ability to control the position and motion of the trunk over the pelvis during running and allows a better force transfer to the terminal segments (22).

Regarding recreational runners, only little research is available about the benefits of strength training on their performance levels (5,21). Because of the increasing number of recreational runners worldwide, who are regularly participating in marathon and half-marathon competitions, knowledge of the specific responses of recreational runners after a training intervention has important implications for the design of training protocols. These responses would dictate the performance demands required to be successful in those kind of events.

Thus, the aim of the present study was to investigate the effects of a concurrent strength (e.g., complex strength training protocol) and endurance training program on running performance and running economy of middle-aged runners during their marathon preparation. We hypothesized a high adaptation potential and response of skeletal muscle function in recreational runners who are not experienced in strength training, even in the case of a low training volume typical for recreational sports (H1). We also hypothesized that the strength training–induced functional responses on the trunk and leg muscles will lead to an improvement of running performance induced by an increased running economy (H2).

**METHODS**

**Experimental Approach to the Problem**

To investigate the hypothesis of the study, a longitudinal and controlled experimental design was used to assess the effects of a concurrent strength and endurance training in recreational runners with no background in strength training, on the development of muscle strength, running performance and running economy during a marathon preparation. A 2 group (endurance running [E] and combined endurance running and strength training program [ES]) pre and posttesting design was used.

After an uncontrolled but monitored 6-month basic endurance training period, an intervention study was conducted over a period of 8 weeks, which used an endurance training volume of about 250 min·wk⁻¹ in both groups (E, ES), supplemented by 120 min·wk⁻¹ (2 × 60 minutes) of strength training for group ES (Figure 1). Endurance training volume was recommended based on the runner’s training history. The strength training volume was limited by the requested maximal time budget of the participants. Endurance running and strength training group used a consistent 4 set by 3–5 repetition heavy strength training protocol for the lower limb, to emphasize neural adaptations while minimizing muscle hypertrophy in an attempt to enhance running economy. For the trunk muscles, a consistent endurance strength protocol that consisted of 3 sets of 20–25 repetitions was used.

![Figure 1. Experimental design.](image-url)
As independent variables we defined the different interventions (E vs. ES) and the 2 measurement points (pre vs. post). The dependent variables were body mass and isometric force (trunk and leg flexors and extensors), endurance capacity (peak maximum oxygen uptake \([\text{VO}_2\text{peak}]\) and anaerobic threshold) and submaximal physiological (oxygen uptake \([\text{VO}_2]\), blood lactate \([\text{LA}]\), heart rate \([\text{HR}]\)) and biomechanical parameters (stride length, stride frequency, ground contact times) at defined moderate running velocities (2.4 and 2.8 m s\(^{-1}\)). We chose these velocities as appropriate to test the study hypothesis because most of the subjects aimed to finish the marathon in about 4–4.50 hours. The treadmill test steps that corresponded closest to the intended marathon pace were 2.4 m s\(^{-1}\) (marathon 4:50 hours) and 2.8 m s\(^{-1}\) (marathon 4:12 hours).

Before pretesting, the subjects were made familiar with all test and training procedures. Postintervention measurements were made 1 week after the final strength training and 2 weeks before the marathon event (Figure 1). The respective rest periods were included to ensure a sufficient taper time for muscle cell and systemic adaptation and to minimize the accumulated fatigue.

**Subjects**

Twenty-two experienced male (\(n = 15\)) and female (\(n = 7\)) recreational runners (mean \(\pm SD\): age 40.0 \(\pm\) 11.4 years; body mass index 22.6 \(\pm\) 2.1; training experience 8.7 \(\pm\) 79 years; basic training volume 4.6 \(\pm\) 1.4 h wk\(^{-1}\)) participated in the study. None of them was experienced in strength training. The participants were randomly separated into 2 groups of 11 runners (ES: 9 men, 2 women and E: 7 men, 4 women) with identical \(\text{VO}_2\text{peak}\) and anaerobic threshold (Table 1). During the intervention period, 2 male runners of the E group were injured and were not included into the statistics, resulting in a final sample size of 20 (ES: 9 men, 2 women and E: 5 men, 4 women). The subjects were familiar with all testing and training procedures before the intervention and gave written informed consent to participate in the study, which was performed in accordance with the ethical standards reported by Harris & Atkinson (16) and conformed to the recommendations of the Declaration of Helsinki. Before participation in the study, subjects were asked to complete a self-administered medical history and physical activity readiness questionnaire to ensure that all the subjects were free of cardiovascular, musculoskeletal, or metabolic diseases.

**Procedures**

*Strength Training.* Strength training lasted for 8 weeks and consisted in 2 training units per week with different contents (Table 2). The first one was designed to improve the motor unit recruitment patterns of the leg muscles by using strength training with high intensity and low volume. Therefore, exercises were performed using 4 sets of maximum number of repetitions of the 3–5RM. Volume determination was performed using time under tension (TUT), which involves monitoring repetition time to perform eccentric and concentric actions during the exercise (37). Therefore, subjects were required to perform an explosive contraction (1-second eccentric, 2-second concentric) resulting in a TUT of about 50 seconds per exercise (Table 2). Overload was provided in the strength training program by constantly increasing the weight lifted, to maintain the same relative resistance.

The second training unit was designed to improve the local strength endurance of the trunk muscles and consisted of 3 sets of low-intensity and high-volume exercises. Therefore, subjects were required to feel subjectively exhausted after 20–25 repetitions in each set. Eccentric and concentric movements were slow and controlled resulting in a much higher TUT (e.g., about 400 seconds) compared with the leg muscle training (Table 2).

All strength training sessions were carried out using Frei (Frei AG, Kirchzarten, Switzerland) and David machines (David Fitness & Medical Ltd., Outukumpu, Finland) and supervised by experienced investigators.

**Endurance Training.** During the intervention period, the endurance training was individually performed by the runners in their usual surroundings. In contrast to the 6-month basic endurance training, the subjects were advised to add...
1 intensive 15-km training unit per week with a running velocity of 90–95% of their expected marathon velocity to ensure specific physiological and coordinative adaptations to the aspired competition pace. Subjects recorded all sports activities in a training log, which was reviewed and analyzed by an experienced investigator. The mean endurance training volume in ES (240 ± 121 min·wk⁻¹) and E (276 ± 108 min·wk⁻¹) was not significantly different during the 2-month intervention period.

**Measurements**

**Incremental Treadmill Run.** VO₂, LA concentration, HR, ratings of perceived exertion (RPEs), and biomechanical parameters (ground contact, stride frequency, stride length) were measured during an incremental treadmill test (Quasar med 4.0 treadmill, hp Cosmos, Nussdorf-Traunstein, Germany). The initial velocity of 2.0 m·s⁻¹ was increased by 0.4 m·s⁻¹ every 5 minutes until exhaustion, with a constant grade of 1%. Blood samples were taken during a 30-second break after each level. Subjects were advised to have no strength or endurance training at least 48 hours before the test and to take a carbohydrate-rich meal 2 hours before testing. All pre and posttests were done in the afternoon between 4 and 7 PM.

Respiratory gas exchange measures were determined using a calibrated mixing chamber system (MetaMax® II, Cortex, Leipzig, Germany). Expired air was continuously analyzed for gas volume (Triple digital-V® turbine), O₂ concentration (zirconium analyzer), and CO₂ concentration (infrared analyzer). Data were transferred by cable and sorted by MetaSoft®. The mean of the 5 highest VO₂ values obtained during the incremental test were used to calculate VO₂ max. The VE/VCO₂ ratio was calculated by dividing the minute ventilation (VE) by the carbon dioxide output (VCO₂) at each workload during the incremental test.

**TABLE 2.** Contents and dosage of the strength training intervention in ES.*

<table>
<thead>
<tr>
<th>Day</th>
<th>Exercises</th>
<th>Sets × repetitions</th>
<th>Weight</th>
<th>Rest between sets</th>
<th>TUT repetition</th>
<th>TUT exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuesday</td>
<td>Leg press; Knee extension; Knee flexion; Hip extension; Ankle extension; Reverse fly; Bench press; Lateral flexion; Trunk extension; Trunk flexion; Trunk rotation</td>
<td>4 × 3–5</td>
<td>3–5 RM</td>
<td>3 min</td>
<td>3 s</td>
<td>48 s</td>
</tr>
<tr>
<td>Thursday</td>
<td>Reverse fly; Bench press; Lateral flexion; Trunk extension; Trunk flexion; Trunk rotation</td>
<td>3 × 20–25</td>
<td>20–25 RM</td>
<td>90 s</td>
<td>6 s</td>
<td>396 s</td>
</tr>
</tbody>
</table>

*ES = endurance running and strength training program; RM = repetition maximum; TUT = time under tension.

**Figure 2.** Pre and postintervention oxygen uptake (VO₂) and running velocity (v) at defined blood lactate (LA) levels during 8 weeks of a combined strength and endurance training (ES) or during endurance training only (E). Analysis of variance (ANOVA) time × intervention: p > 0.10 (effect size d < 0.40).
### Table 3. Changes in relative isometric force during 8 weeks of ES or E.

<table>
<thead>
<tr>
<th></th>
<th>ES</th>
<th>E</th>
<th>p Values</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>Trunk (Nm kg(^{-1}))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexors</td>
<td>1.68 ± 0.38</td>
<td>1.79 ± 0.37 ‡</td>
<td>1.48 ± 0.47</td>
<td>1.37 ± 0.41</td>
</tr>
<tr>
<td>Extensors</td>
<td>2.84 ± 0.45</td>
<td>3.04 ± 0.42</td>
<td>2.39 ± 0.66</td>
<td>2.52 ± 0.67</td>
</tr>
<tr>
<td>Leg (Nm kg(^{-1}))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexors</td>
<td>3.62 ± 0.87</td>
<td>3.96 ± 0.81</td>
<td>3.11 ± 0.67</td>
<td>3.19 ± 0.68</td>
</tr>
<tr>
<td>Extensors</td>
<td>4.60 ± 1.36</td>
<td>6.16 ± 0.97 ‡†</td>
<td>4.57 ± 0.84</td>
<td>4.71 ± 0.72</td>
</tr>
</tbody>
</table>

ES = endurance running and strength training program; E = endurance training.

*Values are given as mean ± SD.
†Significantly different compared with post E.
‡Significantly different compared with pre ES.
§Significant interaction between time and intervention type (p < 0.05).

### Table 4. Changes in physiological measurements at defined \(v\) during 8 weeks of ES or E.*†

<table>
<thead>
<tr>
<th>(v) (m s(^{-1}))</th>
<th>ES</th>
<th>E</th>
<th>p Values</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_O_2) (ml kg(^{-1})·min(^{-1}))</td>
<td>2.4</td>
<td>31.7 ± 1.9</td>
<td>33.3 ± 3.1</td>
<td>32.8 ± 4.3</td>
</tr>
<tr>
<td>2.8</td>
<td>36.9 ± 2.1</td>
<td>37.7 ± 2.9</td>
<td>37.1 ± 3.1</td>
<td>38.8 ± 2.8</td>
</tr>
<tr>
<td>(L_A) (mmol L(^{-1}))</td>
<td>2.4</td>
<td>1.33 ± 0.47</td>
<td>1.17 ± 0.39</td>
<td>1.18 ± 0.67</td>
</tr>
<tr>
<td>2.8</td>
<td>1.75 ± 0.91</td>
<td>1.52 ± 0.81</td>
<td>2.06 ± 1.76</td>
<td>1.81 ± 1.48</td>
</tr>
<tr>
<td>(H_R) (b·min(^{-1}))</td>
<td>2.4</td>
<td>135 ± 14</td>
<td>132 ± 13</td>
<td>139 ± 15</td>
</tr>
<tr>
<td>2.8</td>
<td>149 ± 13</td>
<td>146 ± 13</td>
<td>150 ± 15</td>
<td>147 ± 17</td>
</tr>
<tr>
<td>(R_P_E)</td>
<td>2.4</td>
<td>9.5 ± 2.0</td>
<td>9.1 ± 1.7</td>
<td>9.9 ± 1.5</td>
</tr>
<tr>
<td>2.8</td>
<td>12.1 ± 2.4</td>
<td>11.7 ± 2.5</td>
<td>13.4 ± 2.2</td>
<td>13.6 ± 2.4</td>
</tr>
</tbody>
</table>

*\(v\) = running velocity; \(V_O_2\) = oxygen uptake; LA = blood lactate; HR = heart rate; RPE = rate of perceived exertion; ES = endurance running and strength training program; E = endurance training.
†Values are mean ± SD.
‡Time effect (p < 0.05).
during the test was defined as the peak \( \text{V}_2 \text{O}_2 \) (\( \text{V}_2 \text{O}_2 \text{peak} \)). The volume calibration of the system was conducted before each test day, and the gas calibration was performed before each test using instructions provided by the manufacturer.

Heart rate was monitored every 5 seconds using the S210 (Polar, Kempele, Finland). The mean value throughout the last 30 seconds was taken as reference value for the respective running velocity. For LA analyses, 20 \( \mu \text{L} \) capillary blood samples were taken from the earlobe during the 30-second break immediately after finishing the 5-minute run at each velocity level. Local blood circulation was increased by Finalgon®. Blood samples were hemolyzed in 2-\( \text{mL} \) microtest tubes and analyzed enzymatic amperometrically by the Biosen C-Line Sport (EKF-Diagnostik, Barleben, Germany) immediately after each test. Individual running velocities corresponding to defined LA thresholds were linearly interpolated for 2.0, 2.5, and 4.0 mmol-L\(^{-1}\) (Figure 2). Anaerobic threshold (\( v_4 \)) was defined at 4.0 mmol-L\(^{-1}\) (26). Rating of perceived exertion was obtained using the 15-category Borg RPE scale (6). The scale was explained before the exercise. The subjects were asked: “how hard do you feel the exercise was?" after finishing each velocity level. Biomechanical parameters were measured by using the portable GP MobiData measurement system (Gebiom, Münster, Germany). By means of flexible soles containing 40–64 sensors, the ground contacts and ground forces were continuously measured (200 Hz) and telemetrically transferred to the GP MobiData Software. In the present study, the data for ground contact time, stride frequency, and stride length were statistically analyzed. The calculated values for each running velocity were the mean values of a 10-second measurement interval recorded 30 seconds after starting the level.

**Isometric Strength and Anthropometric Measurements.** Strength training and testing were carried out at the same location using the previously mentioned machines (see “strength training”). The forces developed in a fixed angle position were detected by strain gauges (data collection at 1,000 Hz). Changes in electrical resistance were expressed in Newton (N). The peak torque for the following devices was assessed: F 130 Lumbar and thoracic flexion, F 110 Lumbar and thoracic extension, F 300 Leg Curl, and F 200 Leg Extension. Hip angle during trunk flexion and extension measurements was 90°. The knee angles were 30° for leg flexion and 60° for leg extension measurements. Initially, the subjects completed 10 submaximal dynamic contractions per each measurement, to familiarize with the apparatus. After that, 2 maximal isometric contractions, separated by a 30-second recovery periods, were carried out. Individual body position remained the same throughout all testing procedures. The highest torque achieved during the 2 repetitions was used as peak torque for further statistical analysis. All values were expressed relative to the subject’s weight in Nm-kg\(^{-1}\).

Body weight and height measurements were done before each treadmill test at the same time of the day and under comparable nutritional and pre-exercise conditions. Body weight was measured by a portable approved personal scale without stand (Soehnle 7701, Germany), and height was measured by a simple wall fixed rule. No body composition measurements (e.g., fat free and muscle body mass) were conducted.

**Statistical Analyses**

All data analyses were performed by SPSS for Windows (version 17.0, SPSS, Inc., Chicago, IL, USA). Values are expressed as mean ± SD. After testing the sphericity by using the Mauchly test and in the case of necessity, the Greenhouse–Geisser correction, we calculated a 2-factor analysis of variance (ANOVA) for repeated measurements. Differences between interventions (ES vs. E), time (pre vs. postmeasurement), sex, and interactions between these factors (intervention × time; intervention × time × sex) were calculated. In the case of significance, simple effects were verified by means of a Newman–Keuls test. Significance level was set at \( p \leq 0.05 \). The statistical power was calculated according to Cohen (10) to help protect against type II error.

To determine the meaningfulness of intervention effects, the effect sizes (\( d \)) were calculated for the intervention × time interactions \((i \times t)\) using the pooled SDs as the difference of the pre and posttest effects sizes \( (d_{p} - d_{t}) \). Magnitudes of the effect sizes were interpreted as trivial

**Figure 3.** Pre and postintervention relative oxygen uptake (%\( \text{V}_2 \text{O}_2 \text{peak} \)) at defined running velocities (\( v \)) during 8 weeks of a combined strength and endurance training (ES) or during endurance training only (E). Analysis of variance (ANOVA) time \( \times \) intervention for 2.8 m s\(^{-1}\). \( p = 0.053 \) (effect size \( d = 0.59 \); statistical power = 0.501).
Results

Body Mass and Peak Torque

No changes in body mass occurred during the intervention period (Table 1). Peak torque of leg extensors (ρ = 0.000; effect size = 1.65; statistical power = 0.982) and trunk flexors increased in ES (ρ = 0.012; effect size = 0.61; statistical power = 0.749) verified by significant intervention × time interactions. Peak torque changes of leg flexors and trunk extensors failed to reach the significance level (Table 3).

Endurance Capacity

VO₂peak (ρ = 0.034) and v4 (ρ = 0.004), defined as velocity at 4.0 mmol·L⁻¹ LA, increased significantly during the intervention period (main effect time), whereas no significant between group effects for VO₂peak (ρ = 0.129; effect size = 0.40; statistical power 0.325) and v4 (ρ = 0.322; effect size = 0.15; statistical power 0.161) were found (Table 1).

Running velocity and VO₂ at submaximal LA thresholds (e.g., 2.5 mmol·L⁻¹) were also significantly increased during the intervention period (main effect time). The improvements tended to be stronger in ES, but no group by time interaction and only small effect sizes were calculated for running velocity (ρ = 0.240; effect size = 0.16; statistical power = 0.209) and VO₂ (ρ = 0.093; effect size = 0.40; statistical power = 0.240) at 2.5 mmol·L⁻¹ (Figure 2).

Blood lactate concentrations (2.8 m·s⁻¹) and heart rate (2.4 and 2.8 m·s⁻¹) at defined running velocities were decreased over time, but no group effects were found (Table 4).

Running Economy

VO₂ at submaximal running velocities (2.4 and 2.8 m·s⁻¹) tended to increase during the intervention in both groups (ρ < 0.01) but showed no significant changes (Table 4). VO₂ in relation to one’s VO₂peak tended to decrease in ES and to increase in E with increasing running velocity, leading to a moderate group by time interaction effect for 2.8 m·s⁻¹ (ρ = 0.053; effects size = 0.61; statistical power 0.501) (Figure 3).

Running Coordination

Stride length and stride frequency did not show any changes in ES. In E, stride length was significantly decreased at 2.8 m·s⁻¹ (ρ < 0.05) and stride frequency tended to increase (Table 5). For the ground contact times, a significant group × time interaction was found for 2.4 m·s⁻¹ (ρ = 0.031; effects size = 1.10; statistical power 0.607). Overall, low ICCs were found for ground contact times.

| Table 5. Changes in running coordination and biomechanical measurements at defined v during 8 weeks of ES or E.‡ |
|---|---|---|---|---|
| **ES** | **Pre** | **Post** | **Pre** | **Post** |
| **Intervention** | **Time** | **Effect** | **Size** |
| Stride length (cm) | 2.4 | 92.5 ± 4.7 | 2.8 | 104.7 ± 6.6 |
| Stride frequency (min⁻¹) | 2.4 | 184 ± 11.3 | 2.8 | 156 ± 7.7 |
| Ground contact (ms) | 2.4 | 330 ± 30 | 2.8 | 310 ± 30 |

*Significantly different compared with pre E.†Significantly different compared with post E.
DISCUSSION
The main finding of the present study is that running coordination (e.g., stride length and stride frequency) and the common parameters used for measuring running economy (e.g., \( \text{VO}_2 \) at a submaximal running velocity and \( \text{VO}_2 \) in relation to one's \( \text{VO}_2\text{peak} \)) remained unchanged (rejection of H2) despite a clear improvement of leg strength in response to a low volume strength training feasible by recreational marathon runners (acceptance of H1).

The efficiency of the strength training program conducted in the actual study is particularly revealed in a significant increase of peak torque during the leg extension test (Table 3). Because the mean body mass remained unchanged in both groups (Table 1), a better motor unit recruitment pattern is suggested to be the reason for the increase of leg strength (13,14,30,34,35). Because significant changes in stride length and frequency are missing in the intervention group (Table 5), possible adaptations linked to an improved nervous activation (14,28) were surprisingly not achieved or were not transferred into running technique. However, the correlations between the quality of the stretch–shortening cycle (7,38) or ground contact times (38), respectively, and running economy are not definitely shown in the literature, although they are often postulated (2,28). This is in accordance to the present study in which strength training interventions failed to influence running mechanics in recreational runners.

The central nervous program seems to be more stable and dominant in controlling the running movement compared with the influence of the peripheral muscular effectors. Although we did not find a significant increase in running economy and performance, we were able to show a clear effect on muscle strength that may be advantageous for the endurance runner in a long-term perspective (e.g., by a delayed coordinative transfer or in the prevention of orthopedic overload) (21).

On the first view, running economy seems to be impaired by the strength training intervention because of the slight increase of oxygen uptake at submaximal running velocities (Table 4) that would stand in contrast to previous studies (4,15,18). On the other hand, there are indications that \( \text{VO}_2\text{peak} \) and submaximal \( \text{VO}_2 \), in relation to one's \( \text{VO}_2\text{peak} \), tended to be positively influenced by the strength training program conducted (Figures 2 and 3). Although a significant statistical interaction is missing, a moderate effect size in combination with an insufficient statistical power, point to the risk of a sample size–induced type II error. Thus, it can be speculated that because of an increased peak \( \text{VO}_2 \), the relative \( \text{VO}_2 \) slightly decreased in the ES group, whereas it tended to develop differently in the control group (Figure 3). This would be consistent with previous studies that reported an increase of \( \text{VO}_2\text{max} \) after a strength training program (3,13,30). Several reasons are discussed in that context: An enhanced capillarization and blood flow of the working muscles (12,19,27,30,31), a conversion of muscle fiber structure from type IIB to more oxidative type IIA fibers (34), the innervation of more muscle fibers at low speed as a result of an improved motor unit recruitment (38) and in consequence of these aspects an enhanced fat oxidation on submaximal intensity (2). We assume that the abovementioned physiological muscle adaptations induced by strength training may mask a clear benefit of our intervention on those parameters, usually taken for describing running economy. On the other hand, it obviously seems that the aerobic capacity is not compromised when resistance training is added to an endurance program (19) as speculated before (17,25,36), although more research is needed regarding this topic.

Because of the lack of significant interactions on running technique and running economy between the experimental groups (except a clear effect on peak torque of leg extensors), a precise conclusion is difficult to express. The statistical power of several dependent variables points to an insufficient sample size and the risk of type II errors in our conclusions. The different number of men and women may have influenced the muscle cell adaptation potential in both experimental groups and make any generalizations even more difficult. Finally, we observed several improvements in the endurance training group, which mask the effects in the intervention group and may be affected by an overall increase of training intensity and motivation in the light of the oncoming marathon. However, under the conditions of our study, we have to conclude that running coordination (e.g., stride length and stride frequency) and the common parameters used for measuring running economy do not show clear and definite adaptations, despite a significant improvement of leg strength in recreational marathon runners. Further studies are, therefore, necessary which include a larger sample size and a longer intervention period.

PRACTICAL APPLICATIONS
Recreational marathon runners should be aware that 2 concurrent strength training sessions per week (combination of high intensity training for the lower limb and strength endurance training for the trunk muscles) increase muscle strength and do not impair running performance and running economy. There are even minor indications about positive effects of strength training on endurance performance during such a short mesocycle. Nevertheless, these effects are, respectively, small and mainly based on physiological improvements, whereas the mechanical aspect of running economy seems to be of less importance.

To ensure a better coordinative transfer of strength training effects (adaptation of running technique) and to increase the physiological effects with respect to running economy, a sufficient long strength training period (e.g., 6 month before the marathon or starting already during the basic endurance training period) is recommended for recreational marathon runners. The authors recommend the inclusion of well-structured, periodized strength training programs in their
athletes’ training regimens based on the health and ability of individual athletes during each training phase, combining methods similar to those presented in the article. Besides physiological and biomechanical effects a prevention of an orthopedic overload can be expected.

In addition to the strength training, we recommend an outdoor training of running technique (e.g., running ABC) during the initial stage of the endurance training to close the coordinative gap between strength training and running.

REFERENCES


