Effect of Muscle-Damaging Eccentric Exercise on Running Kinematics and Economy for Running at Different Intensities

Danguole Satkunskienë,1 Arvydas Stasiulis,2 Kristina Zaičenkoviene,3 Raminta Sakalauskaitė,1 and Donatas Raukys1

Institute of Sport Science and Innovations;2 Department of Applied Biology and Rehabilitation; and 3Department of Coaching Science, Lithuanian Sports University, Kaunas, Lithuania

ABSTRACT

Satkunskienë, D, Stasiulis, A, Zaičenkoviene, K, Sakalauskaitė, R, and Raukys, D. Effect of muscle-damaging eccentric exercise on running kinematics and economy for running at different intensities. J Strength Cond Res 29(9): 2404–2411, 2015—The objective of this study was to explore the changes in running kinematics and economy during running at different intensities 1 and 24 hours after a muscle-damaging bench-stepping exercise. Healthy, physically active adult women were recruited for this study. The subjects’ running kinematics, heart rate, gas exchange, minute ventilation, and perceived exertion were continuously recorded during the increasing-intensity running test on a treadmill for different testing conditions: a control condition and 1 and 24 hours after the bench-stepping exercise test. Two muscle damage markers, muscle soreness and blood creatine kinase (CK) activity, were measured before and 24 hours after the stepping exercise. Muscle soreness and blood CK activity were significantly altered (exact p \( \leq 0.05 \), Monte Carlo test) 24 hours after the bench-stepping exercise. The stride length, stride frequency, and support time at different running intensities did not change. Twenty-four hours after the previous step exercise, ankle dorsiflexion in the support phase was significantly higher during severe-intensity running, the range of knee flexion at the stance phase was significantly lower during moderate-intensity running, and knee flexion at the end of the amortization phase was significantly lower during heavy-intensity running compared with the control values (exact p \( \leq 0.05 \), Monte Carlo test). The running economy at moderate and heavy intensities, maximum ventilation, and maximum heart rate did not change. We conclude that, given moderate soreness in the calf muscles 24 hours after eccentric exercise, the running kinematics are slightly but significantly changed without a detectable effect on running economy.

KEY WORDS bench-stepping exercise, delayed onset muscle soreness, treadmill running

Introduction

Various fitness programs that combine long-distance running with aerobic step-bench exercises for improving aerobic physical fitness and body composition are popular among women. Although sports activities and exercises are associated with many beneficial health effects, an evaluation of the injury rates in women who are associated with aerobic exercise (bench-stepping and running) identified 2.44 injuries (grade I–IV) per 100 hours for the running group and 6.09 per 100 hours for the bench-stepping group (44). Most injuries can be classified as overuse injury of the musculoskeletal system (22), resulting from a combined fatigue effect over a period of time beyond the capacity of the specific structure that was stressed (16).

Postexercise muscle soreness after bench-stepping and running is usually associated with damage to connective tissue and myofibrils (11,19); intracellular swelling; increased intramuscular pressure (18); and decreased microcirculation, muscle force (28,29), and functional (6,34) capacity. Nearly 90% of grade I complaints after step-bench exercise are related to delayed onset muscle soreness (DOMS), particularly in the calf region (37,44).

Localized muscle fatigue in the knees and hip extensors and flexors (21,26,40) or in the foot invertors and dorsiflexors (7) can significantly affect the loading rates, peak magnitude, tempo-spatial parameters, and knee and ankle joint motion during running. Changes in the stride length and running kinematics may contribute to an increase in submaximal oxygen consumption in association with exercise-induced muscle damage (3,5).

Running injuries can be caused by muscle imbalance, a restricted range of motion (ROM), the performance level, and the stability of the running pattern (41), especially in less-experienced runners (20). A key factor in maintaining...
stride mechanics despite the onset of fatigue during prolonged running is the ability of the lower limbs to control knee flexion on landing (12,15).

We were unable to locate data on the effect of an eccentric-concentric stepping exercise on running kinematics and economy during running with increasing intensity on a treadmill. To prevent injury, it is important to understand the mechanical responses during running after an aerobic step-bench exercise that is similar to the one that is performed by many people who exercise regularly. Delayed onset muscle soreness peaks after 48–72 hours, but athletes often perform follow-up exercise before this time as a means to reduce the effects of DOMS (36). We specifically examined the effects of eccentric exercise on running during this early period before DOMS reached its maximum.

The objective of this study was to explore the changes in running kinematics and economy during running at different intensities 1 and 24 hours after a muscle-damaging bench-stepping exercise. We hypothesized that the eccentric-concentric stepping exercise would induce calf muscle damage and would change the running kinematics during running at increasing intensity on a treadmill, which would therefore affect the running economy indices 24 hours after exercise.

**Methods**

**Experimental Approach to the Problem**

We tested the hypothesis that a bench-stepping exercise would induce calf muscle damage and change the joint kinematics during running at increasing intensity on a treadmill, affecting indices of running economy 24 hours after exercise using a repeated-measures design. Healthy, physically active adult women were recruited for this study. The subjects’ running kinematics, heart rate, gas exchange, minute ventilation, and perceived exertion were continuously recorded during the increasing-intensity running test on a treadmill for different testing conditions: a control condition and 1 and 24 hours after the bench-stepping exercise. We hypothesized that the eccentric-concentric stepping exercise would induce calf muscle damage and would change the running kinematics during running at increasing intensity on a treadmill, which would therefore affect the running economy indices 24 hours after exercise.

**Subjects**

Nine 19- to 32-year-old, healthy physically active female volunteers participated in this study. Mean ± SD values of their body mass, height, and maximum oxygen uptake (V̇O₂max) were 55.53 ± 5.45 kg, 164.0 ± 0.05 cm, and 42.4 ± 3.2 ml·kg⁻¹·min⁻¹, respectively. Before the procedures began, all participants signed an informed consent form, which had been approved by the local Ethics Committee for Biomedical Research (No: BE-2-36).

**Procedures**

On the first day of testing, the subjects performed an increasing-intensity running test as a control. After 5 days, the study was repeated; before the bench-stepping exercise, test blood samples were taken to measure the CK activity and the calf muscle pain was rated. Then, the subjects performed warm-up exercises, which were followed by the bench-stepping exercise. After 1 hour, they performed an increasing ramp running test on the treadmill. After 24 hours, the subjects returned to the laboratory for the third time, and the blood CK activity and calf muscle soreness were measured before the increasing ramp running test.

**Increasing-Intensity Running Test**

An increasing-intensity running test was performed on a treadmill (LE 200 CE, HP Cosmos, H/P/Cosmos Sports & Medical GmbH, Nussdorf-Traunstein, Germany). The initial treadmill velocity was 7 km·h⁻¹. After 3 minutes, the running speed was increased by 0.1 km·h⁻¹ every 6 seconds. While running, the participant provided a subjective evaluation of the perceived effort at the end of each minute of running. The test was stopped when the subject refused to continue running because of fatigue. Directly after running, they rested (lying down) for 5 minutes. On the fifth and the 20th minutes after the increasing ramp running test, blood samples were collected from their fingers to estimate their blood lactate concentration [La].

**Running Economy Indicators**

Pulmonary gas exchange data were collected during the running tests using an Oxycon Mobile portable gas analyzer (Osycon Mobile; Jaeger, Hoechberg, Germany). The data were analyzed for mean intervals of 5 seconds for all indices using LAB Manager and Microsoft Excel programs. The measurement instrument was calibrated before every test according to the automatic calibration method proposed by the manufacturer (JAEGER, Hoechberg, Germany). The V̇O₂max was measured during the ramp running test by averaging the V̇O₂ for each 15-second interval of the test. The highest V̇O₂ value during the 15 seconds of the increasing running test was considered as the V̇O₂ peak. The relative V̇O₂max was calculated by dividing the absolute index (in L·min⁻¹) by the subject’s body mass. The first (VeT1) and the second (VeT2) ventilatory thresholds were established according to the relationships between the ventilatory equivalents of oxygen, carbon dioxide, and running intensity on the ramp running test (43). The exercise intensities below VeT1, between VeT1 and VeT2, and above VeT2 were considered moderate, heavy, and severe, respectively. The volume of oxygen uptake (ml·kg⁻¹·min⁻¹) during a specific submaximal running intensity (km·h⁻¹) was used to calculate the running economy.

**Bench-Stepping Exercise**

To induce symptoms of muscle damage, after warm-up, the participant performed the stepping exercise on a 0.4-m-high
Effects of Eccentric Exercise on Running Kinematics

step 8 times for 3 minutes during each exercise period. Between stepping, the participant passively rested for 3 minutes by sitting on a bench. The subjects were encouraged to maintain an even stepping tempo according to the rhythm of the music played (120 b·min⁻¹). In the stepping regime, each leg was stepped up and down alternately, ensuring that both legs performed the same concentric and eccentric work. The subjects were instructed to try to land softly on the forefoot during the stepping-down phase to ensure that the eccentric contraction of the calf muscle lasted throughout the entire stepping-down phase.

**Muscle Damage Indicators**

Two indirect markers of muscle damage, DOMS, and blood CK activity were measured before and 24 hours after the stepping exercise. The blood CK activity was measured using a SPOTCHEM EZ SP-4430 analyzer (Spotchem II, ARKRAY, Inc.; Takanna-cho, Nakagyo-ku, Kyoto, Japan). Capillary blood samples of 0.3 ml were obtained from the subject’s finger using an Accutrend lactate single-use device (Boehringer Mannheim, Germany); the skin was disinfected before and after the procedure. Delayed onset muscle soreness was assessed using a visual analog scale from 0 to 10 points. Each number on the scale has the following descriptive words for soreness: 0 (none), 1 (very slight), 2 (slight), 3 (mild), 4 (less than moderate), 5 (moderate), 6 (more than moderate), 7 (intense), 8 (very intense), 9 (barely tolerable), and 10 (intolerably intense).

**Running Kinematics**

Two-dimensional kinematic data were acquired using a Basler A600 video camera and a CONTEMPLAS TEMPLO Standard (CONTEMPLAS GmbH, Kempten, Germany) motion capture system. The camera was placed on a level tripod; therefore, the optical axis of the camera was perpendicular to the treadmill and aligned with the knee. The camera operated at 100 fields per second and was set 4 m away on the participant’s right side. The camera view was calibrated using a 1.5 × 1.2-m calibration frame, which was set parallel with the performance lane and at the midway of the optical axis of the camera. This setting ensured that the calibration area covered the lower limb. The lower limb was viewed as 3 segments (the thigh, shank, and foot). Four light-reflecting markers of 1 cm in diameter were placed on the right leg using an adaptation of the markings identified by Vaughan et al. (42). Anatomical markers were placed on the greater trochanter, lateral femoral epicondyle, lateral malleolus, and head of the fifth metatarsal. The runners were videotaped throughout the ramp running test. The fixed landmarks were digitized automatically by SIMI Motion (Reality Motion Systems GmbH, Unterschleissheim, Germany) software. A 3-point moving average was used for smoothing the markers’ data. The angles chosen for this analysis were hip flexion/extension, which was determined from the thigh and a vertical line; knee flexion/extension, which was determined from the thigh and shank segments; and ankle plantar and dorsal flexion, which was determined by the shank and dorsum of the foot. Plantar flexion, which refers to the movement that increases the angle between the dorsum of the foot and the shank, and dorsal flexion, the movement that decreases the angle between the dorsum of the foot and the shank, were also measured. The period between 2 successive right

<table>
<thead>
<tr>
<th>Indices</th>
<th>Control</th>
<th>1 h after step</th>
<th>24 h after step</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{O_{2}}$ max (ml·kg⁻¹·min⁻¹)</td>
<td>42.4 ± 3.2</td>
<td>40.6 ± 3.6*</td>
<td>42.4 ± 2.8</td>
</tr>
<tr>
<td>$V_{O_{2}}$ at VeT1 (%$V_{O_{2}}$ max)</td>
<td>78.5 ± 7.7</td>
<td>75.6 ± 7.5</td>
<td>75.3 ± 5.0</td>
</tr>
<tr>
<td>$V_{O_{2}}$ at VeT2 (%$V_{O_{2}}$ max)</td>
<td>90.1 ± 6.6</td>
<td>90.7 ± 5.5</td>
<td>88.5 ± 6.5</td>
</tr>
<tr>
<td>VE at VeT1 (L·min⁻¹)</td>
<td>48.6 ± 9.8</td>
<td>45.9 ± 10.0</td>
<td>47.3 ± 7.9</td>
</tr>
<tr>
<td>VE at VeT2 (L·min⁻¹)</td>
<td>67.1 ± 14.1</td>
<td>66.0 ± 13.4</td>
<td>66.6 ± 12.1</td>
</tr>
<tr>
<td>$V_{O_{2}}$ at VeT1 (L·min⁻¹)</td>
<td>1.88 ± 0.224</td>
<td>1.791 ± 0.300</td>
<td>1.663 ± 0.212</td>
</tr>
<tr>
<td>$V_{O_{2}}$ at VeT2 (L·min⁻¹)</td>
<td>2.223 ± 0.283</td>
<td>2.148 ± 0.273</td>
<td>2.191 ± 0.269</td>
</tr>
<tr>
<td>RE below VeT1 (ml·kg⁻¹·km⁻¹)</td>
<td>225.8 ± 14.3</td>
<td>221.9 ± 23.8</td>
<td>227.0 ± 16.4</td>
</tr>
<tr>
<td>RE between VeT1 (ml·kg⁻¹·km⁻¹)</td>
<td>209.3 ± 14.4</td>
<td>211.1 ± 20.3</td>
<td>212.7 ± 14.8</td>
</tr>
<tr>
<td>Max heart rate (b·min⁻¹)</td>
<td>198.1 ± 6.8</td>
<td>195.7 ± 6.3</td>
<td>195.6 ± 12.4</td>
</tr>
<tr>
<td>VE max (L·min⁻¹)</td>
<td>93.3 ± 15.4</td>
<td>89.8 ± 13.0</td>
<td>92.9 ± 11.8</td>
</tr>
<tr>
<td>Max test speed (km·h⁻¹)</td>
<td>13.7 ± 1.1</td>
<td>12.9 ± 1.1*</td>
<td>13.3 ± 1.0</td>
</tr>
<tr>
<td>Max aerobic speed (km·h⁻¹)</td>
<td>13.2 ± 0.9</td>
<td>12.7 ± 1.0*</td>
<td>13.1 ± 0.9</td>
</tr>
<tr>
<td>La 5 min (mmol·L⁻¹)</td>
<td>9.7 ± 2.8</td>
<td>7.7 ± 1.7*</td>
<td>9.0 ± 2.5</td>
</tr>
<tr>
<td>La 20 min (mmol·L⁻¹)</td>
<td>5.4 ± 1.3</td>
<td>4.5 ± 1.1*</td>
<td>5.1 ± 1.6</td>
</tr>
</tbody>
</table>

*Significantly different compared with the control value.

VE = pulmonary ventilation; RE = running economy.
foot ground contacts was used to calculate the stride frequency. The treadmill speed and stride duration were used to calculate the stride length (33). The average values for the stride length, stride frequency, and support time for 3 successive strides, which were measured at different running intensities under different testing conditions for each participant, were used in the analyses. The treadmill was calibrated according to the manufacturer’s recommendations during active running at different speeds. The error in treadmill speed ranged from 0.01 to 0.03 km·h⁻¹, yielding a stride length error of less than ±1 cm.

Hip, knee, and ankle angle data over 1 cycle at the middle of every minute of the ramp running test were selected and analyzed at the following key times: foot strike, support phase maximum knee flexion, support phase maximum foot dorsal flexion, toe-off, and swing phase maximum hip flexion. The ROM for each joint was calculated over the support and swing phases; knee flexion and foot dorsiflexion were measured during the amortization phase (weight acceptance); knee extension and foot plantar flexion were measured during the push-off phase; and hip flexion, knee flexion, and foot dorsal flexion were measured during the overswing phase. Control trial of every participant was digitized twice. We measured hip, knee, and ankle joint angles at 3 instants: foot strike, support phase maximum knee flexion, and toe-off. The average absolute hip angle measurement error was 0.15°, knee angle 0.12°, and ankle angle 0.17°. Additionally, position-time graphs of each joint data over 2 successive cycles of running were analyzed using a modified Bray-Curtis index. The values of modified Bray-Curtis index calculated for the samples were 0.99 for the ankle, 0.99 for the knee, and 0.98 for the hip.

**Statistical Analyses**

Data are presented as mean ± SD. Differences between the results from the various conditions were tested using IBM SPSS version 20. The Wilcoxon signed-ranks test was used to assess the effects of the bench-stepping exercise. Statistical significance was accepted at 𝑝 ≤ 0.05. The exact test was used to compute the significance level of the selected statistics. The 99% confidence interval for 10,000 Monte Carlo samples was chosen to provide the true 𝑝 value within a confidence interval (38).

**RESULTS**

**Muscle Damage Indicators**

All subjects felt pain and tenderness in their calf muscles 24 hours after the previous step exercise; the soreness score varied from 3 to 7 points, and the average score was 4.9 ± 1.8 points. Muscle soreness was significantly altered (𝑝 = 0.003, Monte Carlo test). Blood CK activity was 1,351 ± 0.970 μkat·L⁻¹ before the previous step exercise and significantly higher (2,169 ± 1,331 μkat·L⁻¹) 24 hours after the previous step exercise (𝑝 = 0.004, Monte Carlo test).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>1 h after stepping</th>
<th>24 h after stepping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stride length (in meters)</td>
<td>1.54 ± 0.09</td>
<td>1.88 ± 0.11</td>
<td>2.23 ± 0.22</td>
</tr>
<tr>
<td>Stride frequency (in strides·min⁻¹)</td>
<td>81 ± 5</td>
<td>89 ± 7</td>
<td>92 ± 6</td>
</tr>
<tr>
<td>Support time (s)</td>
<td>0.36 ± 0.04</td>
<td>0.32 ± 0.02</td>
<td>0.29 ± 0.01</td>
</tr>
</tbody>
</table>

*Significantly different compared with the control value.*

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**Table 2.** Stride length (in meters), stride frequency (in strides·min⁻¹), and support time (s) during the increasing-intensity running test before and after the bench-stepping exercise (mean ± SD).
Table 3. Hip, knee, and ankle angles (in degrees) at given times in the running cycle and during the increasing-intensity running test before and after the bench-stepping exercise (mean ± SD).*

<table>
<thead>
<tr>
<th>Joint angle</th>
<th>Key time</th>
<th>Joint</th>
<th>Control</th>
<th>1 h after stepping</th>
<th>24 h after stepping</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Moderate</td>
<td>Heavy</td>
<td>Severe</td>
</tr>
<tr>
<td>Hip</td>
<td>Heel-strike</td>
<td>23 ± 6</td>
<td>26 ± 4</td>
<td>29 ± 5</td>
<td>24 ± 4</td>
</tr>
<tr>
<td></td>
<td>Maximum knee flexion</td>
<td>19 ± 5</td>
<td>22 ± 4</td>
<td>21 ± 6</td>
<td>20 ± 4</td>
</tr>
<tr>
<td></td>
<td>Toe-off</td>
<td>-14 ± 6</td>
<td>-19 ± 5</td>
<td>-24 ± 4</td>
<td>-14 ± 6</td>
</tr>
<tr>
<td></td>
<td>Maximum hip flexion</td>
<td>29 ± 6</td>
<td>32 ± 5</td>
<td>37 ± 6</td>
<td>29 ± 5</td>
</tr>
<tr>
<td></td>
<td>ROM flexion</td>
<td>43 ± 3</td>
<td>51 ± 3</td>
<td>60 ± 5</td>
<td>44 ± 5</td>
</tr>
<tr>
<td>Knee</td>
<td>Heel-strike</td>
<td>159 ± 7</td>
<td>158 ± 7</td>
<td>155 ± 8</td>
<td>158 ± 5</td>
</tr>
<tr>
<td></td>
<td>Maximum knee flexion</td>
<td>130 ± 5</td>
<td>128 ± 4</td>
<td>128 ± 6</td>
<td>132 ± 4</td>
</tr>
<tr>
<td></td>
<td>Toe-off</td>
<td>150 ± 9</td>
<td>151 ± 7</td>
<td>150 ± 7</td>
<td>152 ± 7</td>
</tr>
<tr>
<td></td>
<td>Maximum hip flexion</td>
<td>112 ± 6</td>
<td>108 ± 12</td>
<td>104 ± 12</td>
<td>115 ± 8</td>
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<tr>
<td></td>
<td>ROM stance flexion</td>
<td>28 ± 4</td>
<td>30 ± 4</td>
<td>27 ± 4</td>
<td>26 ± 5</td>
</tr>
<tr>
<td></td>
<td>ROM stance extension</td>
<td>19 ± 6</td>
<td>23 ± 5</td>
<td>22 ± 5</td>
<td>20 ± 8</td>
</tr>
<tr>
<td></td>
<td>ROM swing flexion</td>
<td>57 ± 12</td>
<td>67 ± 12</td>
<td>76 ± 14</td>
<td>60 ± 10</td>
</tr>
<tr>
<td>Ankle</td>
<td>Heel-strike</td>
<td>100 ± 8</td>
<td>101 ± 8</td>
<td>102 ± 8</td>
<td>103 ± 7</td>
</tr>
<tr>
<td></td>
<td>Maximum knee flexion</td>
<td>84 ± 4</td>
<td>85 ± 5</td>
<td>85 ± 6</td>
<td>87 ± 4</td>
</tr>
<tr>
<td></td>
<td>Toe-off</td>
<td>119 ± 11</td>
<td>126 ± 10</td>
<td>127 ± 9</td>
<td>121 ± 10</td>
</tr>
<tr>
<td></td>
<td>Maximum hip flexion</td>
<td>102 ± 7</td>
<td>105 ± 9</td>
<td>109 ± 10</td>
<td>104 ± 6</td>
</tr>
<tr>
<td></td>
<td>ROM dorsiflexion</td>
<td>19 ± 6</td>
<td>20 ± 5</td>
<td>20 ± 6</td>
<td>19 ± 6</td>
</tr>
<tr>
<td></td>
<td>ROM plantar flexion</td>
<td>38 ± 9</td>
<td>45 ± 8</td>
<td>45 ± 8</td>
<td>37 ± 9</td>
</tr>
<tr>
<td></td>
<td>ROM swing</td>
<td>17 ± 7</td>
<td>21 ± 6</td>
<td>18 ± 6</td>
<td>17 ± 10</td>
</tr>
</tbody>
</table>

ROM = range of motion.
†Significantly different compared with the control value.
Running Economy Indicators
During the ramp running test that was performed 1 hour after the previous step exercise, the VeT2 (p = 0.024), max test speed (p = 0.036), VO2max (p = 0.049), and [La] at 5 minutes (p = 0.007) were significantly lower than for the control test. These variables returned to baseline levels during the ramp running test that was performed 24 hours after the previous step exercise. Running economy at moderate and heavy intensities, maximum ventilation, and maximum heart rate did not differ between the 2 ramp running tests after the previous step exercise compared with the control ramp running test (Table 1).

Running Kinematics
The stride length increased and stride frequency decreased significantly during the heavy-intensity running performed 1 hour after the previous step exercise (p = 0.022 and 0.029, respectively, Monte Carlo test). Twenty-four hours after the previous stepping exercise, the stride length, stride frequency, and support time at the moderate, heavy, and severe running intensities did not change (Table 2).

When the joint kinematics was compared before and 24 hours after the step exercise, significant changes were observed. Ankle dorsiflexion at the support phase was significantly higher during the severe-intensity running (p = 0.021, Monte Carlo test). The range of knee flexion at the stance phase was significantly lower during the moderate-intensity running (p = 0.04, Monte Carlo test). Knee flexion at the end of the amortization phase was significantly lower during the heavy-intensity running (p = 0.05, Monte Carlo test) (Table 3).

Discussion
In our study, we investigated for the first time the effect of bench-stepping on running kinematics and economy for running at different intensities on a treadmill 1 and 24 hours after exercise. Based on previously published studies, we hypothesized that the step aerobics training protocol used in our study would induce muscle damage. Newham et al. (31,32), Larsen et al. (28), and Fredsted et al. (17) investigated the effects of bench-stepping and reported that subjects experienced pain, tenderness, morphological changes, and a decreased maximal voluntary contraction force in the quadriceps, adductors, and gluteus muscles of 1 leg and the calf muscle of the other. In our study, the subjects felt moderate soreness in the calf muscles. This different muscle response to step exercise might be due to the differences in the exercise protocols. In previous studies, the subjects stepped up and down from a bench such that 1 leg was always used to step up and the other was always used to step down. In this format, the quadriceps and gluteus muscles of the step-down leg and the contralateral calf muscles contract eccentrically to support the subject’s weight while lengthening during the step-down. In our study, the stepping regime ensured that both legs underwent the same concentric and eccentric work because each leg was alternately used to step up and down.

Postexercise muscle soreness is usually associated with damage to connective tissue and myofibrils (11,19), intracellular swelling, increased intramuscular pressure (18), and decreased microcirculation and muscle force capacity (28,29). Typical statements found in the literature are that soreness is usually perceived approximately 24–72 hours (45) after eccentric-concentric muscle contractions (28). In our study, 2 subjects reported mild pain, 1 reported less than moderate pain, 5 reported more than moderate, and 1 experienced intense soreness in the calf muscles 24 hours after the bench-stepping exercise. The blood CK activity was increased in all subjects (by 88.9% on average, with interindividual variations from 18 to 28.3%). Large variations in the CK response among the women after exercises that induce muscle damage have been reported by others authors as well (17). This variation can be attributed to changes in the CK activity with different estrogen levels in the menstrual cycle (39), which we could not control in our study.

Muscle damage can induce greater reliance on anaerobic energy production, which may contribute to a change in the running economy during DOMS (4). Running economy is defined as the energy cost of running at a submaximal velocity (10). The increase in the submaximal oxygen associated with exercise-induced muscle damage may be explained in part by changes in the motor unit recruitment related to muscle damage and/or local muscle fatigue (3,4,14), in which the active skeletal muscle fibers are unable to generate sufficient force, and additional motor units must be recruited to maintain a given level of work. In our study, the greatest changes in the VO2max, VeT2, maximal test speed, and maximal blood lactate concentration were observed 1 hour after previous exercise, and these variables returned to baseline levels during the ramp running test that was performed 24 hours after previous step exercise. We found that previous stepping exercise induced calf muscle damage that did not significantly affect the oxidative muscle capacity during running 24 hours after previous step exercise. The running economy at moderate and heavy intensities, maximum ventilation, and maximum heart rate did not differ between the 2 ramp running tests after the previous step exercise compared with the control ramp running test.

The metabolic cost of submaximal running at a constant speed is influenced by various factors including fatigue and kinematic characteristics such as the step length and frequency (23). Alterations in the stride length and running kinematics have also been associated with exercise-induced muscle damage (3,5,27). In our study, calf muscle damage 24 hours after the previous stepping exercise did not affect the stride length, stride frequency, or support time during running at different intensities. The increased stride length and decreased stride frequency 1 hour after previous exercise could be associated with fatigue.

In our study, engaging in previous stepping exercise, which induced calf muscle damage as indicated by DOMS...
and elevated CK activity, increased the range of ankle dorsiflexion at the support phase in the ramp running test, but this change was only at a severe running intensity. Jones et al. (24) showed that exercises that induce calf muscle damage (e.g., walking backward down an inclined treadmill) affect type 2 fibers more severely than type 1 fibers. Because type 2 fibers are recruited at intensities above the lactate threshold (1), the increased range of ankle dorsiflexion in the support phase at the severe running intensity could be explained by the decreased eccentric contractile force of the foot extensors because of damage to the sarcoplasmic reticulum (8) within type 2 fibers. This idea is supported by the finding that after eccentric exercise, a longer muscle length is needed to achieve the same myofilament overlap and force production because of an increase in the series compliance due to the overextended sarcomeres (30,35). This increased length could explain our observation that the range of ankle dorsiflexion at the stance phase increased significantly with increasing running intensity only 24 hours after the stepping exercise.

The stepping exercise influenced the knee joint kinematics during running at moderate and heavy intensities. The range of knee flexion angles at the stance phase and at the end of the amortization phase decreased significantly 24 hours after the bench-stepping exercise. Fatigue or muscle damage could make it difficult to control the lower limb during foot contact (13,25,26). In the kinematic chain, the motion of 1 segment influences the motions of adjacent segments. In the lower leg, the plantar flexors of the ankle work eccentrically to control the forward momentum of the leg over the foot at the early stance phase and facilitate heel lift. A decrease in knee flexion at moderate and heavy running intensities may have prevented calf muscle pain during muscle stretching (9) at the amortization phase. The decrease in the ROM at the knee during weight acceptance (40) reduces tension in the calf muscles. By contrast, the increased knee flexion at contact may have reflected an attempt to reduce the risk of injury because increasing the knee flexion angle at ground contact can reduce the peak vertical ground reaction impact force (12,13).

These findings suggest that changes in the ankle and knee joint kinematics 24 hours after the previous stepping exercise do not affect the stride length, stride frequency, support time, or economy during running. These findings support the hypothesis that kinematic parameters cannot explain the complexity of running economy (2,27).

We conclude that performing a bench-stepping exercise in which each leg is alternately used to step up and down induces calf muscle damage that causes moderate DOMS 24 hours after exercise. The following changes were observed in the joint kinematics during running: increased ankle dorsiflexion at the support phase during severe-intensity running, decreased range of knee flexion at the stance phase during moderate-intensity running, and decreased knee flexion at the end of the amortization phase during heavy-intensity running. We found that previous stepping exercise induced calf muscle damage that did not significantly affect the stride length or frequency, running economy, maximum ventilation, or heart rate during running at different intensities 24 hours after exercise.

**Practical Applications**

Running is one of the most common forms of human locomotion used in almost all sport events, and various fitness programs that combine long-distance running with different types of eccentric exercises induce DOMS. Peak muscle soreness is usually perceived approximately 48–72 hours after the eccentric-concentric muscle contractions, and many athletes, after eccentric exercise, use next day running to treat DOMS. According to the findings of this study and given the moderate soreness in the calf muscles 24 hours after eccentric exercise, people can run when experiencing DOMS but should be aware that their running characteristics may be slightly altered.

**References**