MUSCLE INJURY AFTER LOW-INTENSITY DOWNHILL RUNNING REDUCES RUNNING ECONOMY

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ABSTRACT

Baumann, CW, Green, MS, Doyle, JA, Rupp, JC, Ingalls, CP, and Corona, BT. Muscle injury after low-intensity downhill running reduces running economy. J Strength Cond Res 28(5): 1212–1218, 2014—Contraction-induced muscle injury may reduce running economy (RE) by altering motor unit recruitment, lowering contraction economy, and disturbing running mechanics, any of which may have a deleterious effect on endurance performance. The purpose of this study was to determine if RE is reduced 2 days after performing injurious, low-intensity exercise in 11 healthy active men (27.5 ± 5.7 years; 50.05 ± 1.67 V\textsubscript{O\text{peak}}). Running economy was determined at treadmill speeds eliciting 65 and 75% of the individual’s peak rate of oxygen uptake (V\textsubscript{O\text{peak}}) 1 day before and 2 days after injury induction. Lower extremity muscle injury was induced with a 30-minute downhill treadmill run (6 × 5 minutes runs, 2 minutes rest, −12% grade, and 12.9 km·h\textsuperscript{−}1) that elicited 55% V\textsubscript{O\text{peak}}. Maximal quadriceps isometric torque was reduced immediately and 2 days after the downhill run by 18 and 10%, and a moderate degree of muscle soreness was present. Two days after the injury, steady-state V\textsubscript{O\text{2}} and metabolic work (V\textsubscript{O\text{2}}·L·km\textsuperscript{−}1) were significantly greater (4–6%) during the 65% V\textsubscript{O\text{2peak}} run. Additionally, postinjury V\textsubscript{O\text{2}}, V\textsubscript{E} and rating of perceived exertion were greater at 65% but not at 75% V\textsubscript{O\text{2peak}}, whereas whole blood-lactate concentrations did not change pre-injury to postinjury at either intensity. In conclusion, low-intensity downhill running reduces RE at 65% but not 75% V\textsubscript{O\text{2peak}}. The results of this study and other studies indicate the magnitude to which RE is altered after downhill running is dependent on the severity of the injury and intensity of the RE test.

KEY WORDS eccentric contraction, muscle damage, muscle soreness, downhill run, oxygen consumption

INTRODUCTION

The physiological characteristics that contribute to successful distance running performance have been the topic of numerous studies. The most common variables studied include maximal oxygen uptake (V\textsubscript{O\text{max}}), lactate or ventilatory threshold, running economy (RE), and anaerobic power and capacity (1, 4, 27). The relative impact of each physiological index in predicting running performance is dependent on many factors including the homogeneity of the study’s participants and the distance of the event. For example, in trained runners with similar V\textsubscript{O\text{max}} the relative contributions of the other physiological characteristics become predictive of performance. In particular, RE, the energy demand for a given submaximal running velocity, tends to be highly variable among individuals with matched V\textsubscript{O\text{max}} values, making it a strong predictor of performance (15, 24, 25). In addition, RE is better in endurance-trained individuals and more influential on performance as race distance increases (24, 25). The superior RE found in these individuals is likely related to the increased stress placed on the musculature through training. However, this stress often results in exercise-induced skeletal muscle injury that can acutely influence RE (3, 9, 11).

Skeletal muscle injury is the result of unaccustomed exercise, such as running downhill or running at a higher intensity or longer duration to which the individual is adapted (6, 26). Downhill running predisposes skeletal muscle to eccentric muscle actions (i.e., muscle lengths while active) that result in greater damage than that of isometric or concentric contractions (21, 28). Exercise-induced muscle injury is characterized by delayed onset muscle soreness, inflammation, myocellular damage, increased presence of muscle proteins in the blood, and compromised muscle function (13, 28). Reduced muscle function can be seen as a decline in isometric and isokinetic strength for days to weeks after the injury (9, 11, 28). The diminished muscular strength necessitates recruitment of a greater muscle mass to maintain a given submaximal exercise intensity (21) that manifests itself as an elevation in energy expenditure. The increase in metabolism after injury results in the consumption of more oxygen for a particular workload and thus a reduction in RE occurs (3, 9, 11).
Running economy at treadmill speeds eliciting 65–90% of the subjects’ peak rate of oxygen uptake (VO_{2,peak}) are reduced to 3–12% two to three days after exercise-induced skeletal muscle injury (3,9,11). In these studies, the injury was the result of running downhill on a treadmill for 30 minutes at 70% VO_{2,peak} (3,9,11). Although these studies show a clear relationship between exercise-induced muscle injury and RE after moderate intensity downhill running (e.g., 70% VO_{2,peak}), little is known about the effects of low-intensity downhill running. Therefore, the purpose of this study was to assess RE before and 2 days after a 30-minute bout of running downhill on a treadmill at 55% VO_{2,peak}. We hypothesized that low-intensity (55% VO_{2,peak}) downhill running would result in skeletal muscle injury and reductions in RE, but to a lower extent to what others reported during moderate intensity downhill running (70% VO_{2,peak}) (3,9,11). From a practical perspective, the results from this study are beneficial to coaches in 2 ways. First, they help them to understand how low-intensity downhill running, similar to what a runner might experience during easy running on courses with large elevation changes or a hill workout that requires the athlete to jog back down the hill, affects muscular strength and RE. Second, they give insight into how they may want to structure workouts to optimize future performances.

**METHODS**

**Experimental Approach to the Problem**

To test the hypothesis that low-intensity downhill running (55% VO_{2,peak}) would result in skeletal muscle injury and reductions in RE, a group of 11 recreationally active men were recruited for this study. To ensure testing consistency and retest reliability, a repeated measures experimental design with participants reporting to the laboratory on 4 separate occasions was used. On the first visit, height, body mass, and body composition were recorded. Body composition was determined using dual-energy X-ray absorptiometry (Lunar Prodigy; General Electric, Madison, WI, USA). After these anthropometric measures, participants undertook a maximal treadmill test. Upon completion, a maximal voluntary contraction (MVC) familiarization trial was performed on a 500H Kincom isokinetic dynamometer (Chattanooga Group, Hixson, TN, USA). Three to 7 days later, the participants returned and completed the second MVC familiarization trial followed by a pre-injury submaximal treadmill test. On the third visit, 1 day later, the participants performed a downhill run (i.e., negative grade) to induce skeletal muscle injury. Immediately before and after the injury, the participants reported their degree of muscle soreness and performed MVC tests. Participants were given 2 days to recover before the final and fourth visit, when muscle soreness and MVC were reassessed, and a postinjury submaximal treadmill test was completed. Throughout the duration of testing, participants were instructed to maintain their regular physical activity patterns and refrain from strenuous exercise. Participants were further advised from treating symptoms of exercise-induced muscle injury with any potential aids (e.g., cryotherapy, nonsteroidal anti-inflammatory drugs, etc.). Subjects were asked to adhere to their regular diet, although dietary monitoring was not performed.

A motorized treadmill (Q65; Quinton Instrument Co., Bothell, WA, USA) was used for both the maximal and submaximal treadmill tests, as well as the downhill run. During the tests, gas exchange was continuously measured using an automated gas analysis system (TrueOne 2400 Metabolic Measurement System; Parvomedics Inc., Sandy, UT, USA), and heart rates were recorded using short-range radio telemetry (Polar Electro, Kempele, Finland). Before each test, the metabolic cart’s flow meter was calibrated using a 3-L Hans Rudolph Syringe, and the gas analyzer was calibrated with gases of known concentrations (4% CO₂, 16% O₂). We have previously observed a coefficient of variation of 2.3% (% CV = SD/mean × 100) in VO_{2} measured during repeated treadmill tests at similar intensity used in this study (n = 52 subjects over at least 2 tests; unpublished data).

### Subjects

All the participants were recreationally active in sports, such as soccer, running or tennis, at least 3 times a week, 45 minutes per day for at least 3 months preceding the study. The study participants were not necessarily trained runners and none were elite runners. The study participants were not placed on a uniform diet or hydration schedule. Additionally, testing occurred during various portions of the day but was scheduled per subject at approximately the same time of the day. During all laboratory testings, the subjects were vocally motivated. Descriptive characteristics of the participants are reported in Table 1. Participants completed a medical history questionnaire who were free of any medical limitations and gave informed consent. All procedures were approved by the Georgia State University Institutional Review Board for the Protection of Human Subjects.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean ± SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>27.5 ± 1.7</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.79 ± 0.01</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>83.8 ± 3.1</td>
</tr>
<tr>
<td>Body Fat (%)</td>
<td>19.6 ± 2.4</td>
</tr>
<tr>
<td>VO_{2,peak} L·min⁻¹</td>
<td>4.17 ± 0.18</td>
</tr>
<tr>
<td>ml·kg⁻¹·min⁻¹</td>
<td>50.05 ± 1.67</td>
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*VO_{2,peak} = peak rate of oxygen uptake.*
Muscle Injury Reduces Running Economy

Procedures
A maximal treadmill test was used to identify the participants’ VO2peak. The protocol began on a level treadmill at 6.0 km·h⁻¹ and increased to 13.0 km·h⁻¹ by stage 6. During the seventh stage, a 4% inclination was added to the treadmill. After the seventh stage, speed continued to increase and a 2% grade was added every subsequent stage. All stages were 2 minutes in duration.

To determine if downhill running affected RE, a pre-injury and postinjury submaximal treadmill test was performed. The tests required participants to run at 2 different intensities for 10 minutes each on a level treadmill; first at a speed eliciting 65% VO2peak and then 75% VO2peak, with a 15-minute recovery period between runs. Expired gases and heart rate were measured continuously throughout each run. Steady-state VO2, VCO2, minute ventilation (VE), and heart rate were measured and determined from the data collected during the last 3 minutes of each run. Baseline values were subtracted from the exercise response to indicate changes in active metabolism. Total VO2, VCO2, and VE values were also determined as the integral of each response over the entire 10-minute run. The total VO2 was then divided by the total distance run (in kilometers) to estimate metabolic work (L·km⁻¹). Additionally, work of breathing (Wb) and oxygen consumption of the respiratory muscles (VO2 rm) were estimated using the following equations (14):

\[ W_B = -0.430 + 0.0504 \cdot V_E + 0.00161 \cdot V_E^2 \]

\[ V_{O2 \, rm} = 34.9 + 7.49 \cdot W_B, \]

where \( V_E \) is the measured steady-state minute ventilation.

In addition to analyzing RE, rating of perceived exertion, blood lactate, and steps taken were measured. Rating of perceived exertion was reported at the end of each 10 minutes run on a category scale of 6–20 (2). Steps were manually counted during the fourth and ninth minute of each run. These 2 values were then averaged and multiplied by 10 to estimate the total number of steps taken during the 10 minutes run. Immediately before and 2 minutes after each run, blood was collected from each participant through finger stick and analyzed for whole blood lactate (YSI 2300 STAT PLUS; YSI Inc., Yellow Springs, OH, USA). Additionally, serum creatine kinase (CK) activity was measured before and 2 days postinjury as described previously (20).

To induce lower extremity muscle damage, the participants performed an intermittent downhill run. The protocol required participants to run at a 12.9 km·h⁻¹ on a −12% graded treadmill. The downhill run lasted a total of 30 minutes that was divided into 6 intervals of 5 minutes each with a 2 minutes standing rest between each interval. The average VO2 during the downhill run was approximately 55% of the participants’ VO2peak.

The participants reported the degree of muscle soreness of the anterior thigh and posterior lower leg after stepping down from a bench that was 30.45 cm high. Each participant stepped down a total of 4 times from the bench alternating the leading leg between attempts. After each attempt, the participants indicated their soreness on a 100 mm visual analog scale. A score of “0” corresponded to a perception of “no soreness,” whereas a score of “100” indicated a feeling of “very very sore” (10). The mean of the 4 soreness ratings was calculated and used for comparative analysis.

Muscular strength was determined by measuring the participants’ MVC on a 500H Kincom isokinetic dynamometer (Chattanooga Group). The participants were securely placed with their chest, hips, and thighs strapped to the Kincom chair to prevent any extraneous movements during torque production. Standard instructions to produce as much force as possible against the lever arm were given to the participants before testing. After a brief warm-up, the participants were asked to attempt 3 MVCs of a 5-second duration each at 80°, 90°, and 100° of knee flexion with a 45-second rest between each contraction with both the right and left legs separately. For a single leg, participants performed the first 3 contractions at 80°, 90°, and 100° of
Results

The intraclass correlation coefficient for the 2 familiarization
and pre-downhill run strength tests was high ($R = 0.98$)
indicating the participants were familiarized with the
strength protocol and isokinetic dynamometer. For the
pre-injury and postinjury data, the interaction among leg,
angle, or time factors was not statistically significant ($\rho = 0.88$).
The only statistically significant main effect was for
time ($\rho < 0.001$). Therefore, the
average isometric torque value of both legs and all angles
were compared among pre-injury, immediate postinjury,
and 2 days postinjury values (Figure 1) to assess functional
deficits induced by the downhill run. Maximal voluntary
isometric quadriceps torque
was reduced by approximately
18% immediately after the
downhill run. Two days after
the downhill run, strength
began to recover from the
initial deficit but was still approx-
imately 10% lower than pre-injury values. Additionally, a moderate degree of lower extremity muscle soreness and
knee flexion, and then repeated this sequence of contractions
2 more times. The order in which legs were tested varied
among visits. Full extension of the knee was defined as 0° of
flexion. The greatest torque achieved at each angle of knee
flexion for each leg was selected for analysis.

Statistical Analyses

A 3-way repeated measures analysis of variance (ANOVA)
was used to determine if the downhill run altered MVC. A
2-way repeated measures ANOVA was used to detect whole
blood lactate response. Simple effects were analyzed with
separate dependent samples $t$-tests with a Bonferroni corre-
tion. Lower extremity muscle soreness and, for both running
intensities, the remaining pre-injury and postinjury meta-


![Figure 2. Low-intensity downhill running reduced running economy at 65% $V_{\text{O2peak}}$. Steady-state $V_{\text{O2}}$, $V_{\text{CO2}}$, and $V_{\text{E}}$ (A, C, E) and total $V_{\text{O2}}$, $V_{\text{CO2}}$, and $V_{\text{E}}$ (B, D, F) pre-injury and 2 days postinjury. Significantly different from pre-injury (*; $p \leq 0.05$). Values are mean $\pm \text{SEM}$, $N = 11$.](http://example.com/image.png)
was a tendency ($p = 0.08$) for $W_B$ and $V_{O_2 \text{rm}}$ to increase from pre-injury to postinjury ($W_B$, 11.4 ± 0.9 vs. 13.4 ± 1.5 kg·m·min$^{-1}$; $V_{O_2 \text{rm}}$, 120 ± 7 vs. 135 ± 11 ml·min$^{-1}$), suggesting that the energetic cost of breathing was greater during the postinjury run.

During the submaximal treadmill test at 75% $V_{O_2 \text{peak}}$, the participants ran at an average treadmill speed of 11.2 ± 1.0 km·h$^{-1}$, covering a distance of 1.87 ± 0.13 km in 10 minutes for both the pre-injury and postinjury treadmill runs. The estimated number of steps did not change after the injury. Steady-state $V_{O_2}$, $V_{CO_2}$, and total $V_E$, $V_{O_2}$, and $V_{CO_2}$ were not significantly different between pre-injury and postinjury runs (Figure 3). Additionally, ratings of perceived exertion tended to be greater for the postinjury run (13.7 ± 2.0 vs. 14.8 ± 2.0; $p = 0.06$), while steady-state heart rate was similar between pre-injury (170.2 ± 2.2 b·min$^{-1}$) and post-injury (170.0 ± 3.0 b·min$^{-1}$; $p = 0.91$) runs. Blood lactate values were increased above baseline values (reported above) during the pre-injury and postinjury (4.9 ± 0.4 vs. 4.8 ± 0.4 mmol·L$^{-1}$, respectively) 75% $V_{O_2 \text{peak}}$ runs, but there was no statistically significant difference between these values.

**DISCUSSION**

Running economy is an important predictor of distance running performance (25). Exercise-induced skeletal muscle injury as a result of downhill running is known to influence muscular strength and RE (3,9,11). However, little is known about the effects of low-intensity downhill running. Therefore, the objective of this study was to fill in this gap by testing muscular strength and RE after downhill running at 55% $V_{O_2 \text{peak}}$. As we hypothesized, both maximal quadriceps strength and RE were reduced after the injurious downhill run and to a lesser degree to what others have reported at higher intensities (3,9,11). This is the first study to demonstrate that even low-intensity downhill running can impact performance.

During the gait cycle, the quadriceps muscles perform eccentric contractions to decelerate limbs; upon downhill running these eccentric contractions become exaggerated (24). Eccentric contractions generate more torque and activate fewer motor units for a given submaximal load when compared with isometric or concentric muscle actions, and therefore place a high degree of mechanical stress on the activated muscle fibers (18,21,28). The high mechanical stress causes excitation-contraction coupling failure and damage to the muscle's force bearing structures, reducing its ability to produce torque (28). Warren et al. (29) suggest that the force generating capacity of the muscle can be an effective indicator of both the magnitude and time course of the injury. As a result of the downhill run in this study, an 18% strength deficit was observed immediately after the exercise and remained reduced by 10% 2 days postinjury. In addition to a decline in the muscles' force producing capability, CK levels in the blood were significantly elevated and the participants reported increased soreness after the downhill run, typically indicative of inflammation from an immune response (12). Taken together, these results indicate that the low-intensity downhill running protocol was sufficient to induce muscle injury and subsequent physiological and mechanical changes during submaximal running.

Two days after the downhill run, RE at 65% $V_{O_2 \text{peak}}$ was significantly lower, whereas RE at 75% was unchanged. Others have reported that downhill running not only alters RE at 65% but also at intensities ranging from 75–90% (3,9,11). The discrepancy among this study and that of
others (3,9,11) could be because of the intensity of the downhill protocol, and thus the magnitude of muscle injury induced. That is, the participants in this study ran downhill at 55% Vo2peak, whereas those in other studies ran downhill at 70% Vo2peak (3,9,11). The greater downhill running intensity also manifested in greater muscle injury; Chen et al. (9) reported that quadriceps strength was reduced 27.5 and 22.4% immediately and 2 days after their downhill treadmill protocol, whereas we report lesser strength deficits of 18 and 10% at these times (Figure 1). The larger strength deficits reported by Chen et al. (9) in comparison with this study likely reflects greater injury to the susceptible type 2 fibers (19). Therefore, as more motor units are recruited with increasing submaximal running intensity (e.g., from 65 to 75% Vo2peak), a portion of the additional muscle fibers recruited will be injured. In contrast, in this study, it is likely that the majority of the fibers injured during the downhill run were recruited at the 65% Vo2peak running intensity and therefore, few if any additional injured fibers were recruited when transitioning to a higher running intensity (75% Vo2peak). Stated otherwise, as the participants transitioned from the RE test at 65–75% Vo2peak, the motor units recruited to maintain the increased speed of the treadmill belt would have corresponded to high threshold motor neurons that innervated uninjured fibers. We suggest that the recruitment of these additional uninjured fibers at 75% Vo2peak would have masked the inefficient injured fibers’ contribution to steady-state Vo2.

There are several mechanisms that may explain the decrease in RE at 65% Vo2peak. First, a decline in force generation and contraction economy of the injured fibers (30) would necessitate the recruitment of additional motor units (i.e., muscle mass) to maintain a given level of work (16). In support of this, we report a 4.4% rise in metabolic work, whereas others have shown increased electromyographic activity postinjury (16). If the damaged fibers continue to use the same amount of oxygen (16) or consume more as Warren et al. (30) suggest, and the newly recruited fibers consume additional oxygen, the end result would be an increase in submaximal Vo2. Secondly, a change in running mechanics could reduce RE. When running, a preferred stride length is adopted that coincides with optimal efficiency and any deviation from this preferred stride length elevates Vo2 and reduces RE (7). Several studies have observed alterations in stride length and frequency after downhill running (3,9,11). In this study, the calculated number of total steps taken was greater 2 days postinjury, suggesting that stride length decreased. Altered running mechanics may reflect an impaired ability to use the stretch shortening cycle, and therefore, elastic energy (3,11). Lastly, the increased ventilation measured postinjury would result in the respiratory muscles consuming more oxygen. However, we calculate that only 10% of the increase seen in steady-state Vo2 can be accounted for by the increased Vo2 rm from pre-injury to postinjury, suggesting that Vo2 rm did not significantly contribute to the reduction seen in RE. Therefore, it appears that the elevation seen in submaximal Vo2 postinjury is because of several factors, including alterations in motor unit recruitment, contraction economy and running mechanics.

In conclusion, our data agree with previous studies that have demonstrated downhill running induces skeletal muscle injury, and that the injury manifests as decrements in muscular strength and RE (3,9,11). In this study, strength deficits of 18 and 10% were observed immediately and 2 days postinjury. Furthermore, 2 days after the downhill run at 55% Vo2peak, RE at 65% Vo2peak was significantly lower than pre-injury, whereas RE at 75% Vo2peak remained the same. The results of this study and other studies (3,9,11) suggest that the magnitude and intensity at which RE is altered is dependent on the severity of the injury.

**Practical Applications**

Downhill running results in contraction-induced skeletal muscle injury that can be acutely detrimental but chronically advantageous to running performance. Initially, the injurious bout of exercise reduces RE ((3,9,11), this study), a valuable predictor of running success (25). We (this study) report that 2 days after low-intensity downhill running, RE at 65% Vo2peak is reduced by 5.5%, whereas others (9) have shown moderate intensity downhill running reduces RE at 80 and 90% Vo2peak by 7 and 12% at the same time point (i.e., 2 days postinjury). A 5% increase in RE may be related to 3.8% improvement in distance running performance (17), or stated in the opposite direction, a 5% decrease in RE may lead to a 3.8% drop in running performance.

The advantage of the injury is the adaptations that occur after recovery, often termed the repeated bout effect. The repeated bout effect is a protective mechanism, meaning the next time the athlete performs the injurious downhill run, he/she will experience attenuated decrements and faster recovery of muscular strength (5,8,9,11). Chen et al. (8), demonstrated reductions in muscular strength and RE were attenuated after subjects performed the second, identical, downhill running protocol 5 days after the first protocol. More recently, Burt et al. (5) reported similar attenuations to muscular strength and RE after resistance training. By having subjects perform bouts of squats separated by 2 weeks, Burt et al. (5) were able to establish that the initial bout of squats significantly reduced muscular strength and RE, and by allowing the muscles to recover, decrements in muscular strength and RE were blunted or nonexistent after the second bout of squats. This protective response after injury is likely mediated through neural, cellular and mechanical mechanisms (22,23) that can last up to several weeks (5). Therefore, in while acutely after injury the results of the this article and others (3,5,8,9,11) indicate that injurious type exercise reduce RE, in the longer-term the adaptations to the injury may be beneficial to training and performance (31).
Muscle Injury Reduces Running Economy

Knowing that changes in RE are dependent on the time and severity of the injury, coaches should consider scheduling training sessions that stress the muscles eccentrically (e.g., downhill running, squats, etc.) early in the season, and at an intensity sufficient to recruit the fibers that are active during a race. This way, those athletes will have adequate time to recover and adapt from the injurious bout before vital qualifying races. If the athlete(s) are introduced to contraction-induced skeletal muscle injury too close to a race, the coach runs the consequence of reducing the athletes’ chance of success. In closing, many of the aforementioned training concepts are extrapolated to assist high school and collegiate cross-country coaches, but many of the ideas are still salient to novice runners. So regardless of your motivation to run (e.g., competition, weight loss, health, etc.), both the novice and experienced runners must keep in mind that even low-intensity downhill running can injure the muscle, acutely reducing strength and RE, and that training (thus injury) must continually progress to mimic what one would experience in a race.

REFERENCES