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Improvement in Running Economy After 6 Weeks of Plyometric Training

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ABSTRACT

This study determined whether a 6-week regimen of plyometric training would improve running economy (i.e., the oxygen cost of submaximal running). Eighteen regular but not highly trained distance runners (age = 29 ± 7 [mean ± *SD*] years) were randomly assigned to experimental and control groups. All subjects continued regular running training for 6 weeks; experimental subjects also did plyometric training. Dependent variables measured before and after the 6-week period were economy of running on a level treadmill at 3 velocities (women: 2.23, 2.68, and 3.13 $m \cdot s^{-1}$; men: 2.68, 3.13, and 3.58 $m \cdot s^{-1}$), $\dot{V}O_2max$, and indirect indicators of ability of muscles of lower limbs to store and return elastic energy. The last were measurements during jumping tests on an inclined (20°) sled: maximal jump height with and without countermovement and efficiencies of series of 40 submaximal countermovement and static jumps. The plyometric training improved economy ($p < 0.05$). Averaged values ($m \cdot ml^{-1} \cdot kg^{-1}$) for the 3 running speeds were: (a) experimental subjects—5.14 ± 0.39 pretraining, 5.26 ± 0.39 posttraining; and (b) control subjects—5.10 ± 0.36 pretraining, 5.06 ± 0.36 posttraining. The $\dot{V}O_2max$ did not change with training. Plyometric training did not result in changes in jump height or efficiency variables that would have indicated improved ability to store and return elastic energy. We conclude that 6 weeks of plyometric training improves running economy in regular but not highly trained distance runners; the mechanism must still be determined.

Key Words: elastic energy, efficiency, countermovement jump, static jump, stretch-shorten cycle

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Introduction

Economy of running refers to the oxygen cost of running. Economy may be expressed as the rate of oxygen consumption ($\dot{V}O_2$) for a given running velocity (e.g., $ml \cdot kg^{-1} \cdot min^{-1}$), the volume of oxygen consumed per distance covered (e.g., $ml \cdot kg^{-1} \cdot m^{-1}$), or the distance covered per volume of oxygen consumed (e.g., $m \cdot ml^{-1} \cdot kg^{-1}$). Conceptually, better economy refers to running a greater distance for a given volume of oxygen consumed or to consuming less oxygen while running a given distance.

Economy is one determinant of successful performance in distance running (12). Scientists have identified a number of factors that may be associated with running economy, including sex, training status and fitness, age, mechanical variables (e.g., stride length, distribution of segmental masses), distribution of muscle fiber types, heart rate, minute volume of ventilation, and ability of muscle to store and return elastic energy (7).

The ability of muscles to store and return elastic energy effectively is important in movements that involve the stretch-shorten cycle (SSC) (19–21). An SSC is the combination of an eccentric muscle contraction followed immediately by a concentric contraction. Many human movements, including running, involve SSCs. The SSC provides a physiological advantage in that the muscular force developed during the concentric contraction is potentiated by the preceding eccentric contraction (5, 11, 19–21). In other words, the muscle generates more force and is more efficient (i.e., does more work per unit of metabolic energy input) during the concentric contraction when compared with the same contraction without the preceding eccentric contraction. This potentiation has been attributed by some to the storage and return of elastic energy (4, 19, 20). The force generated within the prestretched elements of muscles is added to the force of the concentric contraction, without a proportionate increase in metabolic energy requirement.

Plyometric training is a type of training that is used to enhance the ability of muscles to generate power. Plyometric training exaggerates the SSC, using activities such as jumping, hopping, and bounding. Plyometric training has been shown to improve jumping ability and other high-power movements (8, 10, 15). This suggests that plyometric training improves the ability of muscles to return elastic energy during the SSC, but no direct evidence of this has been presented. If plyometric training does improve the ability of muscles to store and return elastic energy during the SSC, such training should also improve running economy. No previous study of this hypothesis has been found.

This study determined whether a 6-week program of plyometric training improves running economy of regular but not highly trained distance runners. We also measured selected indirect indicators of the ability of muscles to store and return elastic energy, to determine whether they were affected by the plyometric training.

Methods

Experimental Approach to the Problem

Subjects were randomly assigned to 2 groups, separately by sex: an experimental group that trained for 6 weeks with plyometric training and a control group that did not do plyometric training. Subjects in both groups continued their usual running training, and all did the same tests. Each subject completed a battery of tests at 3 different times: test session 1, at initiation of the study; test session 2, 1–2 weeks after session 1 and immediately before the start of the 6-week treatment period; and test session 3, after the 6-week treatment period. All except 1 experimental and 2 control subjects were tested within 3 days after the 6-week treatment period. Because of schedule conflicts, these 3 subjects continued their assigned training for 1 more week before doing the posttraining tests. The same variables were measured in every subject in every test session and in the following sequence: (a) variables related to ability of muscles to store and return elastic energy, (b) running economy, and (c) $\dot{V}O_2$max. Procedures used to measure these variables are described below.

The primary research hypothesis was that the 6-week program of specific plyometric exercises added to regular running training would improve running economy. A 6-week period was chosen because 4- to 8-week cycles of training targeted at specific training goals are common; also, changes in economy have been demonstrated after as little as 3 weeks of specific training (25). Because this specific hypothesis had not been addressed previously and because changes with training are most difficult to demonstrate in the highly trained, runners who were not highly trained were studied. Ultimately, this hypothesis should be tested in athletes competing at the highest levels, although the question is of interest to individuals competing at all levels. But in this first test of the hypothesis, this study was designed to increase the chances of observing an effect of plyometric training if there was one.

Table 1. Characteristics of subjects.*

	Experimental subjects (6 female, 4 male)	Control subjects (4 female, 4 male)
Age (y)		
Men	34 ± 12	27 ± 5
Women	29 ± 7	28 ± 6
All subjects	31 ± 9	27 ± 5
Height (cm)		
Men	174 ± 11	181 ± 4
Women	168 ± 6	166 ± 8
All subjects	170 ± 8	174 ± 10
Weight (kg)		
Men	70.3 ± 14.2	82.1 ± 17.0
Women	62.1 ± 5.0	61.0 ± 6.6
All subjects	65.4 ± 6.8	71.5 ± 6.3
Body mass index ($kg \cdot m^{-2}$)		
Men	23.1 ± 0.7	24.7 ± 0.9
Women	22.0 ± 2.0	22.0 ± 2.6
All subjects	22.4 ± 1.6	23.4 ± 3.7

* Values are means ± *SD*s.

Subjects

Twenty-one volunteers (11 women and 10 men) were originally accepted as subjects and assigned to experimental ($n = 11$) and control ($n = 10$) groups. Two control subjects (a woman and a man) and 1 male experimental subject discontinued participation. Therefore, the final sample consisted of 8 men and 10 women. The 3 subjects who discontinued did so voluntarily, for personal reasons, very early in the study; none quit because of injury or other adverse experiences. Selected characteristics of subjects are summarized in Table 1. All subjects met the criteria of the ''apparently healthy'' category, as defined by the American College of Sports Medicine (1). For at least 6 months before the study, every subject had been training in distance running on a regular basis, defined as averaging at least 10 miles and 3 sessions of running per week. All subjects were nonsmokers. To have some standardization of the metabolic states of subjects during testing, each was asked to refrain from the following for the indicated time periods before testing: eating (≥2 hours), caffeine ingestion (≥4 hours), and vigorous or uncustomary exercise (≥24 hours).

The University's Human Subjects Investigation Committee approved the study. All subjects gave informed written consent before participation.

Training

All subjects were instructed to continue their regular running training as they had done for the 6 months before starting the study and to not begin any new training. In addition to their regular running, experimental subjects were assigned a regimen of plyometric training 3 times a week for 6 weeks. (As noted earlier, 1 experimental subject trained for 7 weeks.) Each session of plyometric training involved 6 exercises done in the following order: (a) warm-up with submaximal double-leg vertical jumps done continuously at about 50% of maximal effort; (b) double-leg vertical power jumps (intermittent); (c) single-leg vertical power jumps with double-leg landing (intermittent); (d) submaximal double-leg vertical springing jumps (continuous vertical jumps of 6–8 in. using minimal knee and hip action and emphasizing the calf action); (e) maximal split-squat jumps done continuously; and (f) submaximal double-leg springing jumps on an inclined surface (intermittent vertical springing jumps of about 6–8 in. done facing uphill on a 6–8% grade such that on landing the balls of the feet make first contact with the surface and the ankle continues to dorsiflex until the heels contact the surface; then concentric contraction of the gastrocnemius-soleus complex is immediately initiated to begin the takeoff of the next jump).

Table 2 contains a summary of the number of repetitions of each exercise during the 6 weeks of training.

Before the start of the training period, experimental subjects were thoroughly instructed on how to do the plyometric exercises, including demonstration and supervised practice. They were also given logbooks listing the regimens by day and week, and each experimental subject kept a written record of running, plyometric training, and any other exercise done throughout the study period. Control subjects also kept written logs of running and other exercises. Experimental subjects were contacted periodically throughout the training period to check on compliance.

Table 2. Summary of the 6-week plyometric training regimen.

	Exercise*	Repetitions
Week 1	Warm-up vertical jumps	10
	Vertical jumps	5
	One-legged vertical jumps	5 with each leg
	Vertical springing jumps	15
	Split-squat jumps	5/5 alternating leading leg
	Incline jumps	10
Week 2	Warm-up vertical jumps	10
	Vertical jumps	8
	One-legged vertical jumps	5/5
	Vertical springing jumps	20
	Split-squat jumps	8/8
	Incline jumps	15
Week 3	Warm-up vertical jumps	10
	Vertical jumps	10
	One-legged vertical jumps	8/8
	Vertical springing jumps	25
	Split-squat jumps	10/10
Week 4	Warm-up vertical jumps	10
	Vertical jumps	12
	One-legged vertical jumps	8/8
	Vertical springing jumps	25
	Split-squat jumps	15/15
	Incline jumps	20
Weeks 5–6†	Warm-up vertical jumps	10
	Vertical jumps	15
	One-legged vertical jumps	10/10
	Vertical springing jumps	30
	Split-squat jumps	20/20
	Incline jumps	25

* Exercises are described in the text.
† Weeks 5–7 for one experimental subject.

Data Collection Procedures

Tests of Running Economy. Economy of running on a horizontal treadmill was measured at 3 velocities in the order listed: 2.23, 2.68, and 3.13 $m \cdot s^{-1}$ for women and 2.68, 3.13, and 3.58 $m \cdot s^{-1}$ for men. Treadmill speed was calibrated before each running bout and verified during each bout. The subject ran for 6 minutes at each velocity and rested between consecutive bouts. Per-minute $\dot{V}O_2$ was measured during each of the last 3 minutes of each bout. The average of the 2 values that differed least from each other was used as the economy measure. Economy was expressed as meters run per milliliter of oxygen consumed per kilogram of body weight ($m \cdot ml^{-1} \cdot kg^{-1}$). This unit allows comparisons across various running speeds, and it has a conceptual advantage in that numerical values are directly related to economy (i.e., the larger the number the better the economy).

Tests of Muscular Ability to Store and Return Elastic Energy. The following variables were the indirect indicators of the ability of extensor muscles acting at the hips, knees, and ankles to store and return elastic energy: (a) difference between the height of a maximal jump with a countermovement (countermovement jump [CMJ]) and the height of a maximal jump without a countermovement (static jump [SJ]), (b) ratio of maximal CMJ height to maximal SJ height, (c) difference between CMJ efficiency and SJ efficiency, and (d) ratio of CMJ efficiency to SJ efficiency (25). These indicators were measured during tests of jumping on an inclined sled similar to the sledge ergometer described by Kaneko et al. (18) but without a force platform on the baseboard. This sled provides standardization of body position during movements similar to normal vertical jumps. The subject sits in a semireclined position on a padded seat with a backrest and with hands placed on handles located on either side of the sled. Arm and trunk movements during jumping are eliminated. The 29.5-kg sled moves on low-friction bearings along 2 tracks that are at a 20° angle with respect to horizontal. The sled ergometer is fitted so that a computer-based data acquisition system computes sled position in real time. Sled excursions during jumping are used to calculate vertical displacement (i.e., height of each jump) and work. Vertical jump height is calculated as (sine of track angle) × (maximal excursion point − starting point). Positive external work in joules is calculated as (mass of sled + mass of subject [in kilograms]) × (maximal excursion point − minimal excursion point) × (sine of track angle) × (9.8 $J \cdot kg^{-1} \cdot m^{-1}$).

Maximal jumping heights were determined before the efficiency tests. Countermovement jumps were done first. After several submaximal warm-up jumps, the subject did a series of at least 5 maximal jumps with brief rest intervals between jumps. The highest jump was recorded as the CMJ height. During all CMJs, the sled's lowest excursion point was measured. The lowest excursion point during the trial with maximal height was used as the starting point for the SJs. For the tests of SJ height, the subject lowered to this point (controlled by a stop), paused in this position for 3 seconds, and then attempted to produce a maximal jump. Using the same protocol as with CMJs, the highest of at least 5 trials was recorded as the subject's SJ height.

Efficiencies of CMJs and SJs were determined by measuring the net oxygen costs of 2 series of jumps. Before the first series of jumps, baseline $\dot{V}O_2$ was measured with the subject seated at rest on the sled but in a prejump position, supporting body and sled weight with the legs, with feet against the baseboard of the sled. After allowing time for $\dot{V}O_2$ to stabilize, baseline $\dot{V}O_2$ was calculated as an average value over at least 3 minutes. After baseline $\dot{V}O_2$ was determined, the subject did a series of 40 CMJs, doing each jump immediately and without hesitation after landing from the previous jump (i.e., with SSCs). The subject attempted to consistently jump to a height of 20% of his or her maximal CMJ height. Continuous feedback of jump height and the 20% target height was displayed on a computer monitor that the subject watched during jumping. The $\dot{V}O_2$ was measured during jumping, and postexercise $\dot{V}O_2$ was measured with the subject resting in the same position as during the prejump baseline $\dot{V}O_2$ measurement period. The $\dot{V}O_2$ was measured postexercise until it returned to the baseline value; this time of measurement varied among subjects from 4 to 13 minutes.

After recovery from the series of CMJs, the subject did a series of 40 SJs. Each SJ started from the average minimum excursion point of the sled during the series of CMJs, and the target jump height was 20% of the maximal SJ height. With each SJ, the subject landed as in any jump but then paused in the lowered position (with the sled supported by the stops) for 3 seconds before doing the next jump. This eliminated the SSC. Height was displayed on the computer monitor, as during the CMJs. After completing the 40 SJs, recovery $\dot{V}O_2$ was measured as it was after the series of CMJs.

The total volume of oxygen consumed during a series of jumps and recovery above the baseline value was calculated to indicate the net oxygen cost of the exercise. Oxygen cost was converted to work in joules: oxygen cost (ml) × 20.92 J × milliliter^{-1}. Efficiency was calculated as percent efficiency = 100 × (positive external work) × (energy cost)$^{-1}$.

Test of $\dot{V}O_2$max. The $\dot{V}O_2$max is an important determinant of success in distance running. It is a common indicator of functional capacity and is affected by different types of training. Therefore, $\dot{V}O_2$max is a standard measurement in training studies related to endurance. In this study, $\dot{V}O_2$max was measured after a rest period after the tests of running economy. Thus, the economy runs served as warm-up for the $\dot{V}O_2$max test, and choice of running velocity in the $\dot{V}O_2$max test was based on the subject's response to the highest velocity of the economy runs. Velocities in $\dot{V}O_2$max tests ranged from 3.58 to 4.92 $m \cdot s^{-1}$ for men and from 3.13 to 4.02 $m \cdot s^{-1}$ for women. The $\dot{V}O_2$max test involved intermittent bouts of running on the treadmill at a constant velocity with progressively increasing positive grades. The grade of the first bout was 2.5–7.5%, depending on the velocity and the estimated fitness of the subject. Grade was increased by about 2.5% with each subsequent bout. Each bout was 3 minutes in duration unless the subject chose to stop sooner. The subject rested for 10–20 minutes between consecutive bouts. The $\dot{V}O_2$ was measured during the last 30 seconds of each bout. The test ended either when the $\dot{V}O_2$max leveling-off criterion was achieved (i.e., measured $\dot{V}O_2$ was no higher in a bout than it was in the previous bout) or when the subject was too fatigued to continue. If the latter occurred, the subject came back within 3 days and ran additional bouts until the leveling-off criterion was met. Of those subjects who required a second day to attain or verify $\dot{V}O_2$max, none took more than 2 bouts.

Measurement of $\dot{V}O_2$. Standard procedures were used in all measurements of $\dot{V}O_2$. The subject, with his or her nose clamped, breathed through a mouthpiece connected to a 2-way non-rebreathing valve. During the economy runs and tests on the sled, normal room air was inspired through a dry gas meter and expired air was directed to a mixing chamber. Expired air was continuously pulled from the mixing chamber and through electronic gas analyzers that measured fractions of oxygen and carbon dioxide. The gas meter and analyzers were interfaced with a computer that used Rayfield software to calculate $\dot{V}O_2$ by means of the standard equation involving the Haldane transformation. A slightly different measurement system was used during $\dot{V}O_2max$ tests. During the last 30–35 seconds of each 3-minute bout of a $\dot{V}O_2max$ test, a timed sample of expired air was collected in a Collins 120-L gasometer that measured the volume. The fractions of oxygen and carbon dioxide in this gas were then analyzed with the same electronic analyzers used in the other tests. The $\dot{V}O_2$ was calculated using the standard equation involving the Haldane transformation. Gas analyzers were calibrated frequently during all tests using the same precision gas mixture.

Statistical Analyses

A pretest-posttest randomized groups experimental design was used. The independent variable was the type of exercise training: regular running training plus plyometric training for the experimental group and regular running training only for the control group. The null hypothesis was that the experimental training would have no effect on the dependent variables: running economy, indicators of muscular ability to store and return elastic energy as measured on the inclined sled, and $\dot{V}O_2max$. Possible effects of the independent variable on the dependent variables were evaluated statistically by a 2-way analysis of variance with nonrepeated measures on one factor (treatment groups) and repeated measures on the other factor (time—pretraining vs. posttraining). Results of tests in session 2 were used as the pretraining values. Data from session 1 were not used in statistical analyses. Test session 1 only provided accommodation to testing procedures for the subjects. One-way comparisons of groups in terms of certain variables were done using independent *t*-tests. In all analyses, statistical significance was defined by $p \leq 0.05$. Results are summarized as means ± *SD*s.

Results

Before the training period, experimental and control subjects did not differ in terms of any variable measured. Based on diary records, every experimental subject except 1 complied completely with the prescribed plyometric training program. The exception omitted 1 plyometric session in 1 week and 1 of the 6 exercises during 1 training session. Also, based on diary records, every subject complied with the instruction to maintain the same program of running that he or she followed immediately before the study.

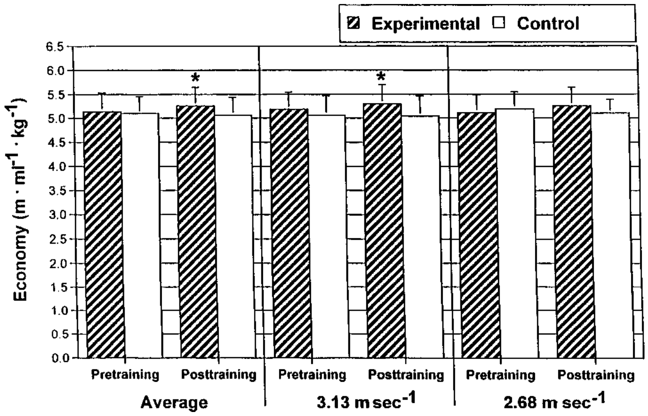

Figure 1. Running economy (average economy at 3 running velocities and economy at 3.13 and 2.68 m·s^{-1}) of experimental (plyometric training) and control (no plyometric training) subjects before and after training period. Values in the graph are means + *SD*s. * indicates significant interaction effect ($p \leq 0.05$); economy of experimental subjects increased over time when compared with control subjects.

The possible effect of plyometric training on running economy was analyzed statistically using 3 economy variables. First, average economy (m·ml^{-1}·kg^{-1}) over all 3 running speeds was calculated for each subject. In addition, economy was analyzed for each of the 2 speeds at which both male and female subjects ran (i.e., 2.68 and 3.13 m·s^{-1}). In general, the plyometric training caused improved economy of running (Figure 1). Average economy improved in experimental subjects when compared with control subjects. Similarly, economy of running at 3.13 m·s^{-1} improved in experimental subjects when compared with control subjects. The numerical results for economy of running at 2.68 m·s^{-1} were similar to the other results, but the difference between experimental and control subjects just missed statistical significance ($p = 0.056$). For experimental and control subjects combined, $\dot{V}O_2$ values (as percentage of $\dot{V}O_2max$) during the economy runs in test session 2 were: men, 56 ± 8% at 2.68 m·s^{-1}, 64 ± 10% at 3.13 m·s^{-1}, and 73 ± 10% at 3.58 m·s^{-1}; women, 57 ± 6% at 2.23 m·s^{-1}, 66 ± 8% at 2.68 m·s^{-1}, and 76 ± 9% at 3.13 m·s^{-1}.

Summaries of height and efficiency results during the jumping tests are presented in Table 3. In every test, each subject jumped higher in the CMJs than in the SJs. There were no differences, however, in either CMJ height or SJ height between groups or over time. In general, efficiency was greater during CMJs than during SJs, but there were 6 isolated tests in which subjects had slightly (≤3.3%) greater efficiencies during SJs than during CMJs. Both CMJ efficiency and SJ efficiency were higher after training than before training for all subjects combined, but the groups did not differ in terms of these variables.

The 4 jumping variables used as indicators of mus-

Table 3. Summary of maximal heights and efficiencies of countermovement jumps (CMJs) and static jumps (SJs) of experimental (plyometric training) and control (no plyometric training) subjects before and after the training period.*

Variables	Pretraining	Posttraining
CMJ height (cm)		
Experimental group	36 ± 7	38 ± 7
Control group	42 ± 9	42 ± 10
SJ height (cm)		
Experimental group	34 ± 7	35 ± 7
Control group	38 ± 9	39 ± 9
CMJ efficiency (%)		
Experimental group	22.9 ± 2.3	25.0 ± 4.2
Control group	21.8 ± 4.6	23.5 ± 2.6
SJ efficiency (%)		
Experimental group	19.3 ± 3.5	22.0 ± 4.7
Control group	18.6 ± 2.5	19.7 ± 3.2

* Values are means ± *SD*s. Height values are vertical distances. There were no statistical differences between groups or from pre- to posttraining, and there were no significant interaction effects.

Table 4. Summary of variables used as indicators of the ability of muscles to use elastic energy in experimental (plyometric training) and control (no plyometric training) subjects before and after the training period.*

Variables	Pretraining	Posttraining
CMJ height-SJ height (cm)†		
Experimental group	2 ± 1	3 ± 1
Control group	3 ± 2	3 ± 3
CMJ height/SJ height		
Experimental group	1.07 ± 0.03	1.08 ± 0.04
Control group	1.10 ± 0.06	1.09 ± 0.07
CMJ efficiency-SJ efficiency (%)		
Experimental group	4.3 ± 2.3	3.6 ± 2.2
Control group	4.0 ± 2.2	4.0 ± 1.8
CMJ efficiency/SJ efficiency		
Experimental group	1.22 ± 0.20	1.16 ± 0.19
Control group	1.17 ± 0.18	1.21 ± 0.12

* Values are means ± *SD*s. Height values are vertical distances. There were no statistical differences between groups or from pre- to posttraining, and there were no significant interaction effects.

† CMJ = countermovement jump; SJ = static jump.

cular ability to store and return elastic energy are summarized in Table 4. There were no differences in any of these variables between groups or over time, and there were no significant interactions. Therefore, based on these indirect indicators, the plyometric training did not improve the ability of muscles to store and return elastic energy.

There were no changes ($p > 0.05$) in $\dot{V}O_2max$ values from pre- to posttraining. Values (in ml·kg^{-1}·min^{-1}) for experimental subjects were 50.4 ± 9.0 pretraining and 50.4 ± 8.0 posttraining; values for control subjects were 54.0 ± 7.2 pretraining and 54.2 ± 6.4 posttraining.

Discussion

The most important finding was that the 6-week program of plyometric training added to regular distance running training improved the economy of running at selected speeds. After searching the literature, we believe that this is the first study to demonstrate that a regimen of plyometric training specifically improves running economy.

The conclusion that plyometric training added to running training improves running economy must be restricted to the conditions of this study. For one thing, our subjects were not highly trained runners. It may be more difficult to improve economy in highly trained runners, who already are very economical as a rule (9). The primary rationale in using less trained runners was the hope that economy would be more easily affected in such subjects. We also used a relatively short-term (6 weeks) and moderate plyometric training program. Our study sheds no light on the possible effects of longer or more intense training programs. With these qualifications, we have concluded that relatively moderate and short-term plyometric training improves running economy in regular, but not highly trained, runners.

The improvement in economy after the plyometric training was small (2–3%), but small differences in economy can be important in competitive distance running. Also, the training program was not intense. It is reasonable to think that greater improvements in economy may be realized with more intense or prolonged training, although this requires verification in future studies. The improved economy occurred independent of a change in $\dot{V}O_2max$. This is important because $\dot{V}O_2max$ typically reaches a peak value for an athlete relatively quickly with training. After this, improvements in endurance performance that depend on physiological adaptations require other changes, such as changes in economy. Based on our findings, one way to improve economy is by way of plyometric training.

The average economy value of all subjects across all running speeds before the training period was 5.12 m·ml^{-1}·kg^{-1}. This value is similar to values reported by many other authors. For example, Bransford and Howley (9) reported values equivalent to 4.78 and 4.98 m·ml^{-1}·kg^{-1} for untrained women and men, respectively, running at 3.13 m·s^{-1} and 5.00 (women) and

5.43 (men) m·ml^{-1}·kg^{-1} for trained runners at that speed. Economy values of elite male distance runners at 4.47 m·s^{-1} have been reported to range from 5.05 to 5.95 m·ml^{-1}·kg^{-1} (24). Our subjects were not highly trained, competitive runners as a group. Further research is needed to determine whether plyometric training enhances running economy is such athletes.

Most studies of training and running economy investigated the effects of running training. Findings have included improved economy (14), no change in economy (6, 14), and decreased economy (23). Johnston et al. (17) found improved economy at 2 running speeds in female distance runners after 10 weeks of strength training. The increases they observed were similar in magnitude to increases in the present study.

Paavolainen et al. (25) studied the economy of well-trained endurance athletes running at 3.67 and 4.17 m·s^{-1} during a 9-week ''explosive-strength training'' program that included plyometric exercises. Economy of running at 4.17 m·s^{-1} improved about 7% after the first 3 weeks of training. The authors did not state whether economy improved further after 3 weeks, and they did not report results of economy at 3.67 m·s^{-1}. Their experimental subjects trained with sprinting and high-speed, low-load weightlifting, in addition to plyometrics, so the specific contribution of plyometric training, if any, could not be determined. It is possible to change running economy within a relatively short period.

Maximal CMJ height was greater than maximal SJ height in every test. This is expected in terms of SSC potentiation of concentric contraction force, although some have reported SJ heights greater than CMJ heights (2, 3, 19). We did not find increased maximal vertical jump height after plyometric training (Table 3) as others (8, 10, 15) had. A plausible explanation for our finding is that the plyometric training program was not extremely intense and not aimed at improving maximal vertical jump. We wanted a training regimen that runners would be more likely to adopt (i.e., that did not take a lot of time and effort), as well as a regimen with relatively low risk of injuries to muscles, connective tissue, and joints. Our training regimen could be completed in 10–15 minutes and could easily be included in warm-up or cool-down activities associated with running workouts. The lack of an effect of the plyometric training on maximal vertical jump may also have been due to differences in mechanics between the jumping exercises done as part of the plyometric training and jumping on the sled. Finally, the failure to find improved jumping ability after the plyometric training may be due to insufficient statistical power.

Although there is much evidence that plyometric training can improve jumping ability and performance of other movements that involve high power and the SSC (8, 10, 13, 15, 16, 22, 26), there has been little research on the mechanisms of such improvement. These mechanisms may include improved return of elastic energy stored during the eccentric phase of the SSC. In this study, plyometric training improved running economy without altering the indicators of the ability of muscles to return strain energy. One possible explanation for this finding is that the improvement in economy occurred by way of a mechanism not involving storage and return of elastic energy. On the other hand, it is possible that the improvement in economy involved enhanced storage and return of elastic energy but we could not detect this with the indirect measurements we used. For example, it may be that the differences between mechanics of jumping on the sled and mechanics of running at the velocities we studied were so great that training-induced changes that affected the running did not affect the jumping. Mechanisms of effects of plyometric training should be a focus of future research.

One may question whether the improved running economy in the experimental subjects resulted from the plyometric exercises per se or simply from the additional 10–15 minutes of intermittent exercise done by those subjects in each training session. We do not think that adding 10–15 minutes of intermittent running, for example, would have improved economy, but we cannot absolutely rule this out. To address this, future studies should use a nonplyometric control exercise, recognizing that selection of appropriate exercise controls is often problematic.

Practical Applications

This study provides support for including plyometrics in the training programs of distance runners to improve running economy. Apparently, relatively moderate plyometric training can increase running economy, which in turn should improve distance running performance. Further research is needed to determine whether more intense or more prolonged plyometric training enhances economy even more and to determine whether specific regimens of plyometric training improve running economy of highly trained distance runners.

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