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SHORT-TERM PLYOMETRIC TRAINING IMPROVES RUNNING ECONOMY IN HIGHLY TRAINED MIDDLE AND LONG DISTANCE RUNNERS

PHILO U. SAUNDERS,[1,4] RICHARD D. TELFORD,[2] DAVID B. PYNE,[1] ESA M. PELTOLA,[1,2]
ROSS B. CUNNINGHAM,[3] CHRIS J. GORE,[1] AND JOHN A. HAWLEY[4]

[1]Department of Physiology, Australian Institute of Sport, Belconnen, Australia; [2]Track and Field Program, Australian Institute of Sport, Belconnen, Australia; [3]Statwise Pty. Ltd., Flynn, Australia; [4]Exercise Metabolism Group, School of Medical Sciences, RMIT University, Bundoora, Australia.

ABSTRACT. Saunders, P.U., R.D. Telford, D.B. Pyne, E.M. Peltola, R.B. Cunningham, C.J. Gore, and J.A. Hawley. Short-term plyometric training improves running economy in highly trained middle and long distance runners. *J. Strength Cond. Res. 20(4): 947–954. 2006.*—Fifteen highly trained distance runners ($\dot{V}O_2$max 71.1 ± 6.0 ml·min^{-1}·kg^{-1}, mean ± *SD*) were randomly assigned to a plyometric training (PLY; $n = 7$) or control (CON; $n = 8$) group. In addition to their normal training, the PLY group undertook 3 × 30 minutes PLY sessions per week for 9 weeks. Running economy (RE) was assessed during 3 × 4 minute treadmill runs (14, 16, and 18 km·h^{-1}), followed by an incremental test to measure $\dot{V}O_2$max. Muscle power characteristics were assessed on a portable, unidirectional ground reaction force plate. Compared with CON, PLY improved RE at 18 km·h^{-1} (4.1%, $p = 0.02$), but not at 14 or 16 km·h^{-1}. This was accompanied by trends for increased average power during a 5-jump plyometric test (15%, $p = 0.11$), a shorter time to reach maximal dynamic strength during a strength quality assessment test (14%, $p = 0.09$), and a lower $\dot{V}O_2$-speed slope (14%, $p = 0.12$) after 9 weeks of PLY. There were no significant differences in cardiorespiratory measures or $\dot{V}O_2$max as a result of PLY. In a group of highly-trained distance runners, 9 weeks of PLY improved RE, with likely mechanisms residing in the muscle, or alternatively by improving running mechanics.

KEY WORDS. oxygen consumption, strength training, elite runners

INTRODUCTION

In highly-trained runners, there are a number of physiological factors that determine running performance, with running economy (RE) identified as a critical factor in distance running performance (28). RE is represented by the energy expenditure and expressed as the submaximal O_2 consumption ($\dot{V}O_2$submax) at a given running speed (2, 7, 8, 24). Runners with good RE use less O_2 than runners with poor RE at the same steady-state speed (9–11). The relationship between RE and performance is well documented, with many independent reports demonstrating a strong relationship between these 2 variables (7–10, 12, 26). Accordingly, it is likely that any improvement in RE will be associated with improved distance running performance. Better RE coincides with a lower O_2 cost at a given running speed. Submaximal O_2 consumption is used as an indicator of RE (2, 7, 8, 24) on the assumption of negligible anaerobic contribution associated with submaximal running speeds. Runners with good RE use less O_2 than runners with poor RE at the same steady-state speed (33). Given the importance of RE in performance, successful training interventions that improve RE would be advantageous for the athlete.

We have recently reported improved RE in elite runners after 20 days of moderate simulated altitude exposure (30). However, many countries may not have appropriate training venues/facilities at altitude, and the use of simulated altitude houses or chambers is even more impractical for most nations. Accordingly, if alternative training techniques can improve RE, they would likely be embraced by coaches and athletes. One such approach is to supplement normal running training with strength/resistance training. Such training has previously been shown to improve RE (20, 23, 25, 31, 34). Specific types of strength training can improve anaerobic power characteristics, such as the ability to produce short contact times and faster force production (3, 19). Heavy resistance training (e.g., full squats) has been reported to improve endurance performance in previously untrained subjects (16, 21, 22), and RE in moderately-trained female distance runners, without concomitant changes in $\dot{V}O_2$max (20). Recent work has shown that a combination of heavy-weight training and endurance training also leads to improved running performance and enhanced RE in well-trained triathletes (23).

A specific type of strength training, known as explosive-strength training or plyometric training (PLY), has been reported to invoke specific neural adaptations such as increased activation of the motor units, with less muscle hypertrophy than typically observed after heavy-resistance strength training (14, 15, 27). PLY enhances the muscle's ability to generate power by exaggerating the stretch-shorten cycle, using activities such as bounding, jumping, and hopping (34). PLY also has the potential to increase the stiffness of the muscle-tendon system, which allows the body to store and utilize elastic energy more effectively (31). Both of these adaptations resulting from PLY could potentially improve RE by generating greater force production from the muscles without a proportionate increase in the metabolic energy requirement. In this regard, Paavolainen et al. (25) reported that in moderately trained runners, 9 weeks of PLY improved RE (8.1%) and 5-km performance (3.1%) with no changes in $\dot{V}O_2$max. Similarly, other studies have also shown improvements in RE and performance with no change in $\dot{V}O_2$max after short-term PLY in moderately-trained subjects (31, 34). To date, however, there is little research investigating the effects of PLY in highly trained distance

TABLE 1. Subject characteristics.*

Group test	Plyometric training group ($n = 7$)		Control group ($n = 8$)	
	Pretest	9 wk	Pretest	9 wk
Age (y)	23.4 ± 3.2		24.9 ± 3.2	
Weight (kg)	67.6 ± 9.7	68.2 ± 9.4	68.0 ± 7.7	68.0 ± 7.7
$\dot{V}O_2$max ($L\cdot min^{-1}$)	4.54 ± 0.53	4.57 ± 0.47	4.75 ± 0.19	4.93 ± 0.38
$\dot{V}O_2$max ($ml\cdot min^{-1}\cdot kg^{-1}$)	67.7 ± 6.2	68.2 ± 7.5	70.4 ± 6.2	72.5 ± 5.0
Training volume ($km\cdot wk^{-1}$)	100.2 ± 48.1		114.1 ± 39.8	
3-km best time (min)	8.6 ± 0.4		8.5 ± 0.4	

* Values are mean ± *SD*.

TABLE 2. Nine-week plyometric training program.

	1		2–5			6–9		
Week session	1	2	1	2	3	1	2	3
Back extension	1 × 15		2 × 15	2 × 15		2 × 15		
Leg press	2 × 6		5 × 8	5 × 8		5 × 8		
Countermovement jumps	1 × 6		3 × 6	3 × 6		3 × 6		
Knee lifts (technical)	1 × 20		3 × 20			3 × 20		
Ankle jumps	1 × 10		3 × 10	3 × 10		3 × 10		
Hamstring curls	1 × 10		3 × 10	3 × 10		3 × 10		
Alternate-leg bounds		1 × 10			6 × 10 m		6 × 10 m	4 × 10 m
Skip for height		1 × 30 m			4 × 30 m		4 × 30 m	5 × 20 m
Single-leg ankle jumps		1 × 20 m			4 × 20 m		4 × 20 m	
Continuous hurdle jumps								5 × 5
Scissor jumps for height								5 × 8

runners. Improving RE and performance in moderately trained male runners (25, 31, 34) may be easier than eliciting similar improvements in highly trained runners, in whom RE and performance are already at a very high level and have attained a plateau. Accordingly, this study determined the effects of the addition of PLY to the normal aerobic running of elite distance runners.

METHODS

Experimental Approach to the Problem

The study was a repeated-measures design with measures conducted prior to and after 5 and 9 weeks of a training intervention period (independent variable). Seven subjects were in the PLY group, and 8 subjects comprised the control (CON) group. Subjects were matched based on performance level, distance run, and prior history of strength training before being randomly allocated into the 2 groups. Prior to intervention, all subjects performed baseline testing of the dependent variables, which included measures of RE at 3 running speeds (14, 16, and 18 $km\cdot h^{-1}$), a maximal test to determine $\dot{V}O_2$max, and strength and power parameters using a variety of jumping protocols on a portable, unidirectional ground reaction force (GRF) plate (Kistler Quattro Jump, Winterthur, Switzerland). The PLY intervention lasted 9 weeks and comprised 3 × 30 minute sessions per week. CON subjects undertook similar running training to PLY subjects without any additional intervention. Total training time was matched for both groups, with the control group completing additional stretching and core stability work to match the extra training in the PLY group.

Subjects

Fifteen highly-trained male distance runners volunteered for this study. Subjects all competed at a national level, with 6 competing internationally (Table 1). The caliber of athletes is demonstrated by the group means for 3-km performance time (8.5 ± 0.4 min) and $\dot{V}O_2$max (71.1 ± 6.0 $ml\cdot min^{-1}\cdot kg^{-1}$). Subjects had minimal prior history of strength training, and this was similar for both groups. Subjects undertook 107 ± 43 km of running per week, with the general training pattern being 3 intense interval sessions on either the track or grass, a long run of between 60 and 150 min, 3 midrange runs of 30–60 min, and 3 to 6 second runs of 20–40 min. Subjects were informed of all experimental procedures and the possible risks involved in participation before their written consent was obtained. The study was approved by the Australian Institute of Sport Ethics Committee.

Procedures

Plyometric Training. The first week of PLY involved familiarization with the various exercises, with only 2 sessions undertaken during this week. Careful attention was given to each subject to ensure good technique for each exercise. The 30-minute sessions were conducted either in the gym or on a grass field. During the initial 4 weeks, there were 2 sessions in the gym and 1 on the grass, and the last 4 weeks consisted of 1 session in the gym and 2 on the grass. The gym sessions included leg press at approximately 60% of 1 repetition maximum, hamstring curls on a hydraulic machine, continuous straight-leg jumps (the same as those used in the testing protocol), squat jumps for maximal height, and fast feet drills (emphasis on short contact time and fast force production). All exercises were carried out with fast eccentric/concentric movements. The grass session consisted of alternate-leg bounding, high skipping, single-leg hopping, double-leg jumping over hurdles, and scissor jumps (Table 2). Subjects were tested after 5 weeks and upon completion of the 9-week intervention.

Treadmill Testing. Running economy was determined by measuring submaximal $\dot{V}O_2$ for 4 minutes at 3 running speeds (14, 16, and 18 $km \cdot h^{-1}$), after a standardized warm-up, on a custom-built motorized treadmill (Australian Institute of Sport, Belconnen, Australia) as described in detail previously (29, 30). Measurement of $\dot{V}O_2$, ventilation ($\dot{V}_E$), heart rate (HR), stride rate (SR) and concentration of blood lactate (Lac) was performed during the RE test. Running economy was defined as the $\dot{V}O_2$ determined during the last minute of each running speed. Four minutes was deemed an adequate time to reach steady state from pilot work, and at the fastest running speed (18 $km \cdot h^{-1}$), runners had been running for 12 min. $\dot{V}O_2$max was determined during an incremental test to volitional exhaustion performed 2 minutes after the third submaximal running speed (29, 30). In our hands, the typical error of measurement (17) of submaximal $\dot{V}O_2$ was 2.4% (29) and $\dot{V}O_2$max was 2.2%. Heart rate was measured by short-range telemetry (Polar Vantage NV, Kempele, Finland) and, on immediate completion of the test, a capillary blood sample was drawn for measurement of Lac.

Blood Handling. Capillary blood samples were collected from the fingertip using an Autolet II (Owen Mumford Ltd. Medical Division, Oxford, England) sterile lancet. Approximately 95 μl of blood was collected into a Clinitube (Radiometer Medical A/S, Copenhagen, Denmark) by capillary action for automated analysis of Lac on an ABL700 Series Blood Gas Analyser (Radiometer Medical).

Force Plate Measures. Subjects performed 2 tests on the GRF plate to determine muscle power characteristics. The first test was a strength quality assessment test (SQAT) and involved a vertical jump from a semicrouched or squat position with the subject holding a 9-kg aluminium bar on his shoulders secured within a Smith machine. Subjects were required to jump vertically into the air from a stationary position, with an initial starting knee angle of approximately 120°. During each jump, care was taken to ensure that the subject maintained an erect posture (head up) and landed toes first, in the same spot as takeoff. Force vs. time functions associated with each jump were generated on software interfaced to the GRF plate. The following parameters were determined for each jump: maximal dynamic strength (MDS), the maximum amount of force imparted onto the force plate; time to reach MDS, the time taken to reach maximum force production, with shorter times indicating better force development; rate of force development (RFD); force at 30 ms (F30ms); force at 100 ms (F100ms); and takeoff time. The second test performed on the GRF plate was a 5-jump plyometric test. This test required the subject to perform 6 maximal continuous straight-leg jumps. Subjects were instructed to aim for maximal height with contact times as fast as possible, keeping legs straight throughout the jumping sequence. Jump height and power were measured during this test both as a mean of the last 5 jumps and the best of the 5 jumps.

Statistical Analyses

A between subject-within subject factorial (group × test × speed) analysis of variance was undertaken. Mean profiles along with standard errors are shown graphically, and the magnitude of variability for each group is indicated by the least significant difference (LSD). Any pair of means differing by more than the LSD was significant ($p \leq 0.05$) between pretests and posttests. The statistical package Genstat (6th edition; VSN International Ltd., Oxford, UK) was employed for statistical computation. Slopes and intercepts of $\dot{V}O_2$ vs. running speed were compared on group mean data using Prism software (version 3.03; GraphPad Software Inc., San Diego, CA). The regression data for the 3 groups were fitted through the measured $\dot{V}O_2$ at 14, 16, and 18 $km \cdot h^{-1}$. The magnitude of difference between changes (9 weeks vs. pretest) in key dependent variables were expressed as an effect size using the following criteria: <0.2, trivial; <0.6, small; <1.2, moderate; and >1.2, large (18).

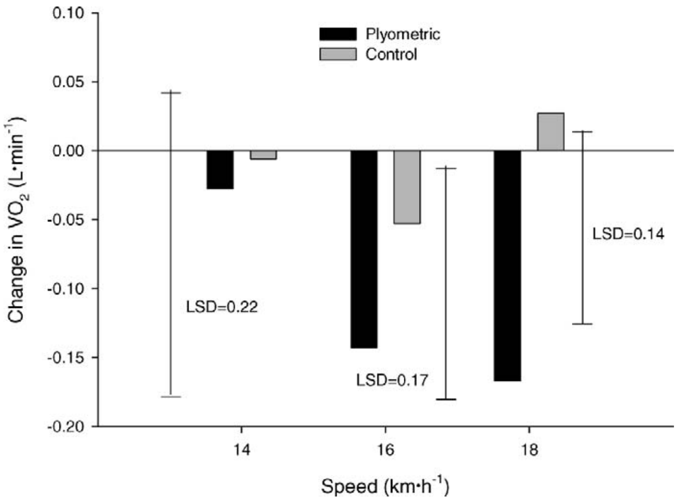

FIGURE 1. Absolute change in O_2 consumption ($L \cdot min^{-1}$) after 9 weeks compared with pretest for plyometric training (PLY) and control (CON) groups at 3 submaximal running speeds (14, 16, and 18 km^{-1}). Values are means; $n = 7$ (PLY), $n = 8$ (CON). Change at 18 $km \cdot h^{-1}$ is significantly different ($p < 0.05$) in PLY, signified by the least significant difference (LSD), because any pair of means differing by more than the LSD are considered significant ($p < 0.05$) changes between pretests and posttests amongst the 2 treatment groups.

RESULTS

Running Economy

Following PLY, the change in $\dot{V}O_2$ at 14 $km \cdot h^{-1}$ was within 0.05 $L \cdot min^{-1}$ of the pretreatment value and was not significantly different after 5 weeks or 9 weeks of intervention. Likewise, there was no significant difference at 16 $km \cdot h^{-1}$ after 5 weeks compared to pretest values. Before and after 9 weeks of PLY the $\dot{V}O_2$ measures were 3.70 ± 0.49 and 3.56 ± 0.48 $L \cdot min^{-1}$ respectively when running at 16 $km \cdot h^{-1}$ ($p = 0.31$). CON had pretest and posttest means of 3.74 ± 0.57 and 3.69 ± 0.53 $L \cdot min^{-1}$ respectively. There was no significant change in RE at 18 $km \cdot h^{-1}$ between pretest and 5 weeks in either group. However, after 9 weeks, $\dot{V}O_2$ was decreased from 4.16 ± 0.51 $L \cdot min^{-1}$ to 3.99 ± 0.46 $L \cdot min^{-1}$ (4.1%, $p = 0.02$), whereas CON remained unchanged at 4.19 ± 0.47 $L \cdot min^{-1}$ and 4.22 ± 0.52 $L \cdot min^{-1}$ (Figure 1). There was no significant change in the slopes of $\dot{V}O_2$ vs. running speed in the preintervention and 9 weeks postintervention slopes for CON. Although it failed to reach statistical significance, there was a trend (13.8%, $p = 0.12$) of a lower slope of $\dot{V}O_2$ vs. running speed after 9 weeks of PLY

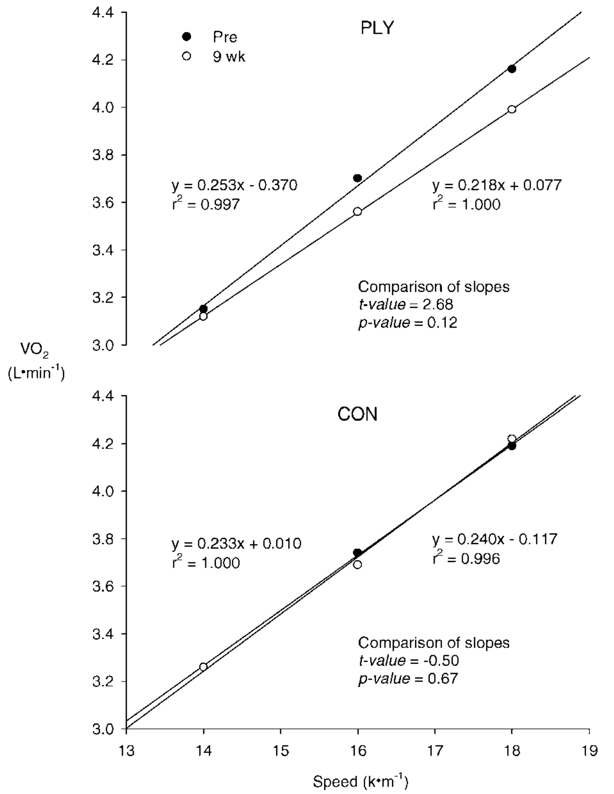

FIGURE 2. Comparison of absolute oxygen consumption ($L \cdot min^{-1}$) with running speed ($km \cdot h^{-1}$) between pretest and posttest for the plyometric training (PLY) and control (CON) groups. Slope equations and r^2 values are given for each slope, as are the t value and p value for the comparison of pretest and posttest slopes for the 3 groups.

(Figure 2). The effect size was trivial at 14 $km \cdot h^{-1}$ and small at 16 and 18 $km \cdot h^{-1}$ in PLY, with trivial effect sizes present at all RE speeds in CON (Figure 3).

Cardiorespiratory and Physiological Measures

Both groups had similar $\dot{V}O_2max$ values before the intervention, and there were no significant changes in this variable after the intervention period (Table 1). There were no significant changes in $\dot{V}_E$, respiratory exchange ratio (RER), HR, SR, or Lac between the 2 groups (Table 3).

Force Plate Measures

There were no differences in the strength and power measures between the 2 groups (Table 4), although the mean value of the F30ms measure tended to be higher ($p = 0.07$) after 5 weeks in PLY. There was also some evidence that the average power during the 5-jump plyometric test was higher (14.7%, $p = 0.11$) (Figure 4), and that the time to reach MDS was lower (14.0%, $p = 0.09$) in PLY compared with the pretest (Figure 5). In the 5-jump plyometric test the effect size for PLY was small for average power and moderate for average height. In the SQAT test effect size for PLY was small for RFD, F100ms, and take-off time, and moderate for time to reach MDS. All selected variables had a trivial effect size for CON (Figure 3).

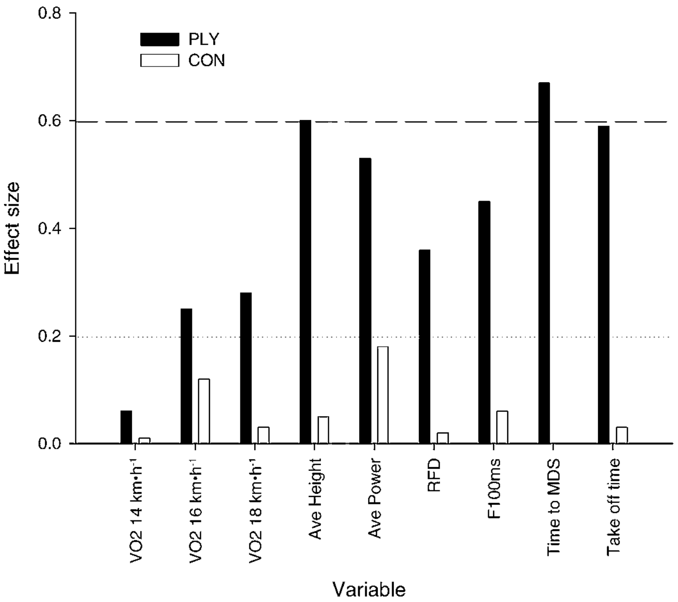

FIGURE 3. Effect sizes of selected variables from treadmill and force plate tests for plyometric training and control groups after 9 weeks compared to pretest. Dashed line = moderate effect (0.60 to <1.20); dotted line = small effect (0.20 to <0.60). RFD = rate of force development; MDS = maximal dynamic strength.

DISCUSSION

The major finding of the present study was that the addition of PLY improved RE at 18 $km \cdot h^{-1}$ by 4.1% in highly trained distance runners when compared to a matched control group undertaking similar running training without PLY. There was no evidence of any change in submaximal RE at slower speeds, however, an examination of the $\dot{V}O_2$ vs. speed slope revealed evidence of a shift in the slope after the plyometric intervention. The improved RE at 18 $km \cdot h^{-1}$ in those runners who supplemented their normal running training with PLY occurred in the absence of any cardiorespiratory changes, and was accompanied by trends towards higher average power production in a 5-jump plyometric test and lower time to MDS in the SQAT analysis compared to CON. To the best of our knowledge, this is the first study to demonstrate improved RE after PLY in a group of elite distance runners.

Our results are in accordance with growing literature demonstrating that a period of strength training improves RE in runners with a wide range of ability (20, 23, 25, 31, 34). However, of these studies, one used moderately-trained female runners (20), another used well-trained triathletes ($\dot{V}O_2max$ approximately 68.0 $ml \cdot min^{-1} \cdot kg^{-1}$) who only ran 44–48 $km \cdot wk^{-1}$ (23), whereas the other investigations used moderately-trained male runners with 5-km performance times of approximately 18 minutes and $\dot{V}O_2max$ of approximately 65.0 $ml \cdot min^{-1} \cdot kg^{-1}$ (25), 3-km performance times of approximately 10 minutes and $\dot{V}O_2max$ of approximately 59.1 $ml \cdot min^{-1} \cdot kg^{-1}$ (31), and $\dot{V}O_2max$ values of approximately 50 $ml \cdot min^{-1} \cdot kg^{-1}$ (34). The current study utilized subjects with superior performance capabilities (3-km performance time, 8.5 ± 0.4 min) and $\dot{V}O_2max$ (71.1 ± 6.0 $ml \cdot min^{-1} \cdot kg^{-1}$) to those in any of the previous investigations. The absence of significant changes in $\dot{V}_E$, HR, RER,

TABLE 3. Cardiorespiratory and physiological variables.*

Group test	PLY			CON			LSD (p value)	
	Pretest	5 wk	9 wk	Pretest	5 wk	9 wk	Pretest–5 wk	Pretest–9 wk
14 km·h^{-1}								
$\dot{V}_E$ (L·min^{-1})	82.0 ± 10.2	86.2 ± 11.2	86.1 ± 16.1	83.5 ± 16.7	86.7 ± 19.2	81 ± 14.8	10.2 (0.86)	7.6 (0.11)
RER (ratio)	0.91 ± 0.03	0.92 ± 0.03	0.91 ± 0.03	0.90 ± 0.05	0.89 ± 0.05	0.88 ± 0.06	0.04 (0.52)	0.04 (0.43)
HR (b·min^{-1})	150 ± 13	147 ± 12	152 ± 11	147 ± 13	145 ± 11	145 ± 12	10.2 (0.84)	12.4 (0.62)
SR (strides·min^{-1})	84.3 ± 2.0	84.2 ± 2.6	84.4 ± 1.4	86.5 ± 4.7	86.4 ± 4	86.4 ± 4.7	2.9 (1.00)	2.3 (0.87)
Lac (mM)	1.9 ± 0.7	2 ± 1.2	2.6 ± 1.4	2.2 ± 1.7	1.9 ± 1.2	2.1 ± 1	1.4 (0.47)	1.7 (0.49)
16 km·h^{-1}								
$\dot{V}_E$ (L·min^{-1})	104.9 ± 13.3	105.7 ± 15.9	107.4 ± 19.4	105.2 ± 24.3	107.2 ± 27.3	98.8 ± 17.6	17 (0.89)	11.4 (0.15)
RER (ratio)	0.97 ± 0.02	0.97 ± 0.04	0.97 ± 0.04	0.95 ± 0.06	0.93 ± 0.06	0.93 ± 0.04	0.04 (0.54)	0.04 (0.29)
HR (b·min^{-1})	166 ± 14	161 ± 10	165 ± 11	160 ± 11	159 ± 12	156 ± 12	10.4 (0.42)	12.6 (0.66)
SR (strides·min^{-1})	86.9 ± 2.8	87 ± 2.8	86.8 ± 2.7	88.2 ± 4.6	88.7 ± 4.8	88.2 ± 5	1.6 (0.65)	1.8 (0.95)
Lac (mM)	2.7 ± 1.4	2.9 ± 2.1	3.1 ± 2	3 ± 2.8	2.7 ± 2.4	2.2 ± 1.4	1.3 (0.75)	1.8 (0.55)
18 km·h^{-1}								
$\dot{V}_E$ (L·min^{-1})	135.9 ± 16.9	131.6 ± 19.5	125.5 ± 21.1	128.9 ± 25.7	135.5 ± 31.6	122.9 ± 22.9	17.9 (0.25)	10.9 (0.44)
RER (ratio)	1.06 ± 0.04	1.03 ± 0.06	1.01 ± 0.05	1.02 ± 0.07	1 ± 0.05	0.98 ± 0.05	0.05 (0.66)	0.06 (0.71)
HR (b·min^{-1})	178 ± 11	174 ± 8	177 ± 10	171 ± 11	171 ± 10	169 ± 11	9 (0.44)	10 (0.79)
SR (strides·min^{-1})	89.6 ± 3.1	89.8 ± 3.3	89.1 ± 3	89.8 ± 4.1	90.7 ± 3.9	89.5 ± 4.5	1.5 (0.36)	1.9 (0.78)
Lac (mM)	5.8 ± 2.8	5.4 ± 3.3	5.9 ± 3.9	5.6 ± 4.7	4.9 ± 3.6	4.1 ± 2.3	1.2 (0.65)	1.7 (0.69)

* Values are means ± *SD* at pretest and after 5 and 9 weeks for plyometric training (PLY) and control (CON) groups at 3 running speeds (14, 16 and 18 km·h^{-1}); $n = 7$ (PLY); $n = 8$ (CON). LSD = least significant difference, which is 2 times the standard error of the differences; any pair of means differing by more than the LSD are considered significant ($p < 0.05$) changes between pretest and posttest amongst the 2 treatment groups. $\dot{V}_E$ = minute ventilation; RER = respiratory exchange ratio; HR = heart rate; SR = stride rate; Lac = blood lactate concentration.

TABLE 4. Strength and power measures.*

Test	PLY			CON			LSD (p value)	
	Pretest	5 wk	9 wk	Pretest	5 wk	9 wk	5 wk	9 wk
5-jump test								
Av jp ht (cm)	41.2 ± 9.8	43.8 ± 7.6	44.6 ± 5.8	39.9 ± 6.9	42.3 ± 6.5	40.1 ± 3.1	4 (0.99)	6 (0.22)
SQAT test								
RFD (N·s^{-1})	21,857 ± 4,903	27,171 ± 14,844	25,254 ± 5,145	21,543 ± 4,539	21,814 ± 5,519	21,887 ± 4,767	9,910 (0.33)	3,200 (0.33)
Time to RFD (ms)	94.4 ± 35.4	83.9 ± 25.9	83.3 ± 32	81.5 ± 25.6	85.6 ± 38.2	71.1 ± 29.4	40 (0.51)	40.8 (0.66)
MDS (kg)	143.8 ± 26.5	151.6 ± 40.2	148.6 ± 32.8	136.4 ± 9.8	141.7 ± 17.2	143.7 ± 18.5	22.4 (0.81)	19.6 (0.58)
F30ms (N)	8.8 ± 3.7	9.8 ± 5.2	8.7 ± 6.6	15 ± 7.9	11.2 ± 7.8	10.3 ± 6.7	5.4 (0.07)	11.2 (0.40)
F100ms (N)	49.5 ± 23.6	62.4 ± 36.9	62.8 ± 34.1	65.7 ± 34.5	65 ± 42	64.9 ± 29.8	31.2 (0.37)	33.8 (0.31)
Takeoff (ms)	261 ± 21	253 ± 39	250 ± 18	254 ± 32	259 ± 48	254 ± 42	35.6 (0.47)	22.2 (0.24)

* Values are means ± *SD* at pretest, 5 weeks, and 9 weeks for the plyometric training (PLY) and control (CON) groups; $n = 7$ (PLY); $n = 8$ (CON). LSD = least significant difference, which is 2 times the standard error of the differences; any pair of means differing by more than the LSD are considered significant ($p < 0.05$) changes between pretest and posttest among the 2 treatment groups. Av jp ht = average jump height from the 5-jump plyometric test; RFD = rate of force development; MDS = maximal dynamic strength; F30ms = force at 30 msec; F100ms = force at 100 msec; Takeoff = time taken to leave the force plate.

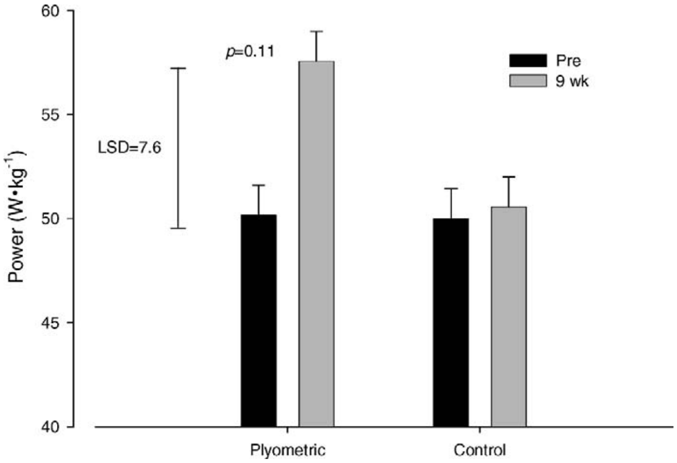

FIGURE 4. Average power in $W{\cdot}kg^{-1}$ for the 5-jump plyometric test at pretest and 9 weeks for plyometric training (PLY) and control (CON) groups. Values are means ± *SE*; $n = 7$ (PLY), $n = 8$ (CON). Least significant difference (LSD) is 2 times the standard error of the differences; any pair of means differing by more than the LSD are considered significant ($p < 0.05$) changes between pretest and posttest among the 2 treatment groups.

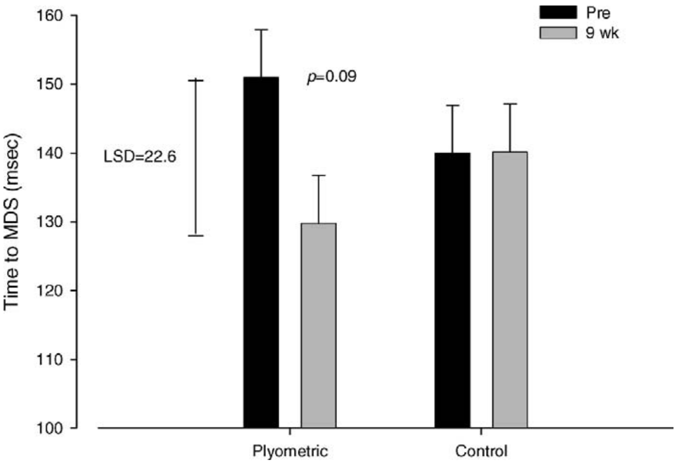

FIGURE 5. Time (msec) to reach maximal dynamic strength (MDS, kg) during the strength quality assessment test at pretest and 9 weeks for plyometric training (PLY) and control (CON) groups. Values are means ± SE; $n = 7$ (PLY), $n = 8$ (CON). Least significant difference (LSD) is 2 times the standard error of the differences; any pair of means differing by more than the LSD are considered significant ($p < 0.05$) changes between pretest and posttest among the 2 treatment groups.

or Lac suggests that the improved RE is not the result of a decreased cardiorespiratory cost or a shift in substrate utilization. Instead, we propose that the trends are toward improved muscular power, suggesting that the underlying mechanisms are related to improved muscle power development and better use of stored elastic energy.

The storage and return of elastic energy is an important component of RE, with estimates indicating that $\dot{V}O_2$ during running might be 30–40% higher without contributions from elastic energy storage and return (6). At higher speeds, elastic mechanisms are reported to prevail over the contractile machinery and may even account for a greater proportion of the work performed (5, 32). This explanation is consistent with PLY's improving RE only at the higher (18 $km{\cdot}h^{-1}$) and not at the lower (14 $km{\cdot}h^{-1}$) speeds in the current study. A key function of the active skeletal musculature during running is to modulate the stiffness of the springs to maximize the exploitation of elastic energy, which improves RE as measured by O_2 consumption (1, 4, 32). Paavolainen et al. (25) demonstrated that 9 weeks of PLY improved RE as well as resulting in concurrent improvement in velocity during a 20-m sprint, improvement in distance covered in a 5-bound plyometric test, and decreased contact times during constant velocity running. Similarly, Spurrs et al. (31) demonstrated that 6 weeks of plyometric training improved the RE of moderately trained runners, with associated improvement in muscle-tendon stiffness and rate of force development during a seated calf raise test.

In the current study, there was some evidence of an increase (14.7%) in average power during a 5-jump plyometric test and a decrease (14.0%) in the time to reach MDS during the SQAT analysis. We speculate that the intensity/volume of PLY in the current study was insufficient to elicit statistically significant improvements in plyometric-related variables. However, there were small and moderate effect sizes after 9 weeks of PLY, and we feel that such improvements are likely to be physiologically important to the elite athlete and result in worthwhile performance enhancements. Caution was taken in the amount of PLY undertaken because the athletes were relatively unfamiliar to this type of training and avoiding injuries was a priority. Likewise, it cannot be excluded that the tests used to measure strength and power in the current investigation were not sensitive enough to detect PLY-induced changes. The inhibiting effects of concurrent strength training and endurance training may also be a mitigating factor in the lack of significant improvements in the plyometric-related variables in the present study.

Another plausible explanation for improved RE after PLY is a training-induced alteration in running mechanics. Indeed, Paavolainen et al. (25) indicated that these alterations occurred in response to PLY. Alterations in running mechanics that allow for better coordination and timing of ground force application would offer a mechanism to improve RE. It may also be that this improvement in whole-body mechanics was evident only at the faster speeds as the runners neared their normal running gait.

At the muscle level, a reduced Adenosine 5'-triphosphate (ATP) cost of contraction, associated with a better elastic energy return, should coincide with a change in slope of the $\dot{V}O_2$ vs. speed relationship. The same is true for a better ATP yield per mol of O_2 used. The slope between $\dot{V}O_2$ and running speed/power output has been used as a means of detecting changes in economy (13). The results of the current study revealed a trend towards a lower (13.8%) slope after 9 weeks of PLY, suggesting that observed improvements in RE is at least partially attributable to improved locomotor muscle metabolism and better elastic energy return. In contrast to this finding, we have previously demonstrated (30) that 20 days of live-high train-low simulated altitude exposure significantly improved RE at 14, 16, and 18 $km{\cdot}h^{-1}$ without any change in the slope of $\dot{V}O_2$ vs. running speed. The improved RE resulting after a period of altitude exposure may have been elicited through enhanced metabolic efficiency rather than improvement in the energy return of the elastic components or the muscle and tendons (24).

In conclusion, we have demonstrated that 9 weeks of PLY improved RE in elite distance runners at speeds typically undertaken by these athletes during training/competition. The mechanisms underlying the improved RE after PLY appear to be unrelated to changes in cardiorespiratory variables or shifts in substrate utilization, suggesting that such enhancements may have been predominantly elicited through enhanced muscular power and elastic energy return, or alternatively through better coordination and timing of ground force application. Although differences in muscle power measures were not significant in the current study, the improved RE at 18 $km \cdot h^{-1}$ is a practically significant result of PLY. Further research is required to determine whether trends we have demonstrated in improving various muscle power measures can be confirmed with PLY of greater volume and intensity, and whether this in turn has a further impact on RE and running performance.

PRACTICAL APPLICATIONS

Although RE has been researched extensively and its importance to performance is unquestioned, there are still relatively few documented training methods that have been shown to improve RE in elite distance runners. The current study, along with findings of our recent study into the beneficial effects live-high train-low simulated altitude exposure have on RE (30), offers specific training interventions that coaches and athletes can implement to improve RE and performance of elite distance runners. Given that well-designed PLY programs have other benefits besides the potential to improve RE, such as improved strength, better running technique, and faster ground contacts, it would seem sensible for coaches to utilize this training method where possible.

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Address correspondence to Philo Saunders, PhD, philo.saunders@ausport.gov.au.