9-2017

Acute Effects of Plyometric and Resistance Training on Running Economy in Trained Runners

Richard T. Marcello
Sacred Heart University, marcellor@sacredheart.edu

Beau K. Greer
Sacred Heart University, greerb@sacredheart.edu

Anna E. Greer
Sacred Heart University, greera@sacredheart.edu

Recommended Citation

Marcello, R., Greer, B.K. & Greer, A.E. (2017). Acute effects of plyometric and resistance training on running economy in trained runners. *Journal of Strength and Conditioning Research, 31*(9), 2432-2437. doi:10.1519/JSC.0000000000001705

Journal of Strength and Conditioning Research Publish Ahead of Print
DOI: 10.1519/JSC.0000000000001705

TITLE: Acute Effects of Plyometric and Resistance Training on Running Economy in Trained Runners

AUTHORS: Richard T. Marcello[1], Beau Kjerulf Greer[1], Anna E. Greer[1]

[1] Department of Physical Therapy and Human Movement Science
Sacred Heart University, Fairfield CT, USA

CORRESPONDING AUTHOR:
Beau Kjerulf Greer
Email: greerb@sacredheart.edu

ABSTRACT

Results regarding the acute effects of plyometric and resistance training (PRT) on running economy (RE) are conflicting. Eight male collegiate distance runners (21 ± 1 years, 62.5 ± 7.8 ml/kg/min $\dot{V}O_2$ peak) completed $\dot{V}O_2$ peak and 1 repetition maximum (1RM) testing. Seven days later, subjects completed a 12 minute RE test at 60% and 80% $\dot{V}O_2$ peak, followed by a PRT protocol or a rested condition of equal duration (CON). The PRT protocol consisted of 3 sets of 5 repetitions at 85% 1RM for barbell squats, Romanian deadlifts, and barbell lunges; the same volume was utilized for resisted lateral lunges, box jumps, and depth jumps. Subjects completed another RE test immediately following the treatments as well as 24 hours later. Subjects followed an identical protocol six days later with condition assignment reversed. RE was determined by both relative $\dot{V}O_2$ (ml/kg/min) as well as energy expenditure (kcal/min). There was a significant ($p < 0.05$) between-trial increase in $\dot{V}O_2$ (37.1 ± 4.2 ml/kg/min PRT vs. 35.5 ± 3.9 ml/kg/min CON) and energy expenditure (11.4 ± 1.3 kcal/min PRT vs. 11.0 ± 1.4 kcal/min CON) immediately post-PRT at 60% $\dot{V}O_2$ peak, but no significant changes were observed at 80% $\dot{V}O_2$ peak. Respiratory exchange ratio (RER) was significantly ($p < 0.05$) reduced 24 hours post-PRT (0.93 ± 0.0) as compared to the CON trial (0.96 ± 0.0) at 80% $\dot{V}O_2$ peak. Results indicate that high intensity PRT may acutely impair RE in aerobically trained individuals at a moderate running intensity, but that the attenuation lasts less than 24 hours in duration.

Key words: cross training, concurrent training, strength training

INTRODUCTION

Running economy (RE) is one of three (along with V̇O$_2$ max and lactate threshold) primary contributors to aerobic performance (4, 6, 13) and is defined as the steady state V̇O$_2$ for a given velocity (28). Assuming steady state aerobic conditions, an individual with superior RE can run faster at a given submaximal V̇O$_2$ compared to an individual with an identical V̇O$_2$ peak (13); differences in RE often explain the performance variance in athletes with comparable aerobic capacities (28).

Numerous studies have shown that chronic resistance training (RT) or plyometric exercise improves RE in runners without negatively affecting aerobic capacity or body mass (22, 26, 30, 35, 38, 40). However, studies directly examining the acute effects of RT on running economy show conflicting results. Doma and Deakin (2014) report no difference in RE 6 hours post-strength training, but a decrease in time to exhaustion running performance after high intensity (6RM) workloads (15). The same authors have also reported that the cost of running at 70% and 90% of ventilatory threshold was significantly greater the day after strength training was performed prior to endurance training (14), but not vice versa. Alternatively, Scott et al. showed no alterations in RE 24-30 hours after a bout of lower body RT (36). In a highly aerobically trained group of runners, RE was impaired at one and eight hours post-RT but not at 24 hours (31). Conversely, Burt et al. report a 4-5% impairment in RE 24-48 hours after an initial bout of squatting-induced muscle damage, although the effect was nonexistent following a subsequent bout of squatting (9). In a review, Assumpção et al. concluded that strength exercises are likely to impair RE only at higher (≥ 90% V̇O$_2$ max) exercise intensities (3).

A smaller body of evidence exists to support the effect of plyometric training alone on RE. Saunders et al. report an improvement in RE at a velocity of 18 km/hr following nine weeks of plyometric training in highly trained runners, although no significant differences were found at slower velocities (35). Six weeks of plyometric training has also been shown to improve RE in a moderately trained subject pool (40). Likewise, nine weeks of low-load, explosive strength training improved RE in highly trained subjects but since this protocol included sprint work it is difficult to ascertain whether the degree to which plyometric work was a contributing factor (30).

Numerous hypotheses exist as to why muscle damage *per se* affects running economy and have been described elsewhere (3). However, rationales for why plyometric or RT may cause an immediate (*i.e.*, prior to the development of secondary, immune-mediated damage) decrease in running economy are less clear. RT causes an increase in glycogen usage and lactate production (17) with a consequent rise in hydrogen ion concentrations. Hydrogen ions dissociate calcium from troponin and interfere with muscle contractions which may result in a reduction of force production (1, 18). Hydrogen ions can also inhibit oxyhemoglobin formation which may result in poor oxygen delivery to working muscles and a greater oxygen demand (39). Additionally, heavy load RT causes neuromuscular fatigue and a reduction in force production (19). This reduction in force production results in reduced muscle stiffness and an impairment of RE (34).

The purpose of the present study was to determine the acute effects of a single, lower-body plyometrics and resistance training (PRT) session on RE in male collegiate distance runners. This investigation is unique in the use of a highly aerobically trained subject pool, the addition of plyometrics to a RT protocol in order to increase external validity of results, as well as measuring RE immediately after the PRT protocol. It was hypothesized that the PRT protocol would cause an impairment in RE lasting at least 24 hours.

METHODS

Experimental Approach to the Problem

The purpose of the present study was to determine the acute (≤ 24 hours) effects of a single PRT session on RE in highly trained distance runners. On two separate occasions, subjects performed a RE test followed by either a PRT workout or rest of equal duration. A high intensity (85% 1RM), moderate volume (6 exercises, 3 sets of 5 repetitions each) training protocol was developed to mimic similar programs used by collegiate cross-country teams as well as those previously used in the scientific literature (26, 38). Subsequent RE tests took place immediately after the intervention as well as 24-hours later. Subjects repeated the protocol six days following the last RE test with the opposing intervention; a crossover design was used as it better controls for reported individual daily variances in RE (7).

Subjects

Before testing commenced, all procedures were approved by the lead author's university Institutional Review Board and all subjects provided informed consent. Nine members of local collegiate cross-country teams volunteered for the study. Subject size was calculated *a priori* via a power analysis using an effect size (0.43) determined during pilot testing. An additional subject was recruited to account for potential attrition.

Subjects (mean age = 21 ± 1 yrs) were required to have engaged in RT at least once in the last three months to ensure uniformity regarding the repeated bout effect (9, 12) and could not be taking any dietary supplements other than multivitamins or minerals. All subjects were running at least six days per week with a range of 50-100 miles per week. Subject characteristics can be seen in Table 1.

Procedures

The study design is represented in Figure 1. Upon first reporting to the laboratory, subject height, weight, and body fat percentage via skinfold technique using Lange Skinfold Calipers (Beta technology, Santa Cruz CA, USA) were measured; the 3-site Jackson Pollock skinfold equation (21) was used to estimate body fat percentage. Participants then underwent a One-Repetition Maximum Test (1RM) in accordance with National Strength and Conditioning Association guidelines (2) for the following three exercises: barbell squats, Romanian dead lifts, and barbell lunges. Subjects completed the eccentric phases of the lifts in three seconds while completing the concentric phase as quickly as possible. Acceptable squat depth was considered to be when the hip and knee joints were equidistant from the floor. The eccentric portion of Romanian dead lifts was executed until subjects could no longer maintain a slightly lordotic curve in the lumbar region. Lunges were considered complete when the front knee reached 90° of flexion and the back knee had barely touched the floor. A 5RM lateral lunge was performed using resistance bands with the goal of fatiguing subjects at five lateral steps of a standard distance (3 feet).

An incremental treadmill running test to volitional exhaustion was used to determine $\dot{V}O_2$ peak. This test, previously used in elite runners (27), entails subjects approximating their 3K race pace for treadmill speed and a progressive increase in grade every two minutes. All metabolic testing was conducted using Parvo Medics TrueOne Metabolic Cart (Parvo Medics, Sandy UT, USA) and a Woodway Desmo treadmill (Woodway USA Inc., Waukesha WI, USA). Subjects did not engage in RT for 72 hours prior to testing, and did not run or consume caffeine or alcohol 24 hours prior to testing. These restrictions were also imposed prior to all subsequent testing procedures. Subjects fasted for four hours before testing and were required to wear the same footwear for all testing procedures.

All subjects performed a continuous 12 minute RE test immediately followed by a PRT protocol or a resting period (CON). The RE test involved six minutes of running at a pace corresponding to 60% $\dot{V}O_2$ peak and, without a rest period, six additional minutes at 80% $\dot{V}O_2$ peak. Only metabolic data from the last two minutes of each stage were analyzed in order to minimize the chance of using non steady-state $\dot{V}O_2$ measurements. Steady-state conditions were further verified by ensuring less than a 10% change in $\dot{V}O_2$ occurred per minute within the collection period (33). These paces were chosen both to mimic common training intensities for the subject pool as well as low enough workloads to ensure steady-state conditions would be met within four minutes. It was a general assumption that an intensity of 80% $\dot{V}O_2$ peak would be below lactate threshold for the highly trained subject pool (5). Due to recent criticisms of solely using relative $\dot{V}O_2$ as the determinant of RE (37), energy expenditure (EE) was calculated for each exercise intensity with use of the respiratory exchange ratio (RER) (23).

The PRT protocol consisted of three sets of five repetitions of barbell squats, Romanian dead lifts and barbell lunges at 85% 1RM with a two minute rest between sets; lateral lunges were completed using resistance bands and step distance that corresponded to the 5RM. Additionally, subjects performed three sets of five repetitions of box jumps and depth jumps with the same two minute rest interval. The same apparatus (45 cm vertical height) was used for both jumps.

Immediately post-PRT or resting period, subjects completed another RE test, identical in methodology to the previous one. An additional (third) RE test took place 24 hours later. All subjects were recommended to eat the same meals at the same time intervals between the second and third RE tests, although dietary intake data was not available for analysis. Six days after the post-24 hour RE test, the groups crossed over and performed the alternate protocol.

Statistical Analysis

All data were tested for normal distribution via a Shapiro-Wilk test. Metabolic data were analyzed parametrically using a repeated measures ANOVA, while *post hoc* analysis was performed via Fisher's LSD test. Order effects were also examined. Effect sizes were calculated as partial eta squared (η_p^2) since repeated measures were used. Significance was set *a priori* at $p < 0.05$, and all data analysis was performed using SPSS V23.0 (IBM; Armonk, NY).

RESULTS

Eight subjects completed all testing procedures; one subject withdrew from the study due to an injury unrelated to this investigation. With the withdrawal of one subject, the order of treatment was equal among subjects with four subjects initially undergoing the PRT protocol and four initially assigned to the CON protocol. No order effects were present ($p > 0.05$).

Data for the 60% and 80% $\dot{V}O_2$ peak RE trials are presented in Table 2 and 3, respectively. At the 60% $\dot{V}O_2$ peak intensity, ANOVA revealed a significant ($p < 0.05$) elevation in $\dot{V}O_2$ ($\eta_p^2 = 0.47$) and EE ($\eta_p^2 = 0.52$) immediately post-PRT as compared to the CON condition. No significant within or between-trial differences were found for $\dot{V}O_2$ (η_p^2 = 0.18; η_p^2 = 0.24, respectively) or EE (η_p^2 = 0.06; η_p^2 = 0.30, respectively) at 80% $\dot{V}O_2$ peak, although a non-significant trend was present for between-trial EE ($p = 0.08$) immediately post-PRT.

No significant differences were found for RER during the 60% $\dot{V}O_2$ peak trial. At 80% $\dot{V}O_2$ peak, RER was significantly ($p < 0.05$) reduced 24 hours post-PRT as compared to the CON trial (η_p^2 = -0.44). There was a non-significant ($p = 0.06$) within-trial trend for RER between the immediately post-CON and 24 hours post-CON time points (η_p^2 = 0.33).

DISCUSSION

The primary finding of the present study was that a high intensity, lower-body PRT protocol significantly reduced RE at a moderate exercise (60% $\dot{V}O_2$ peak) intensity in highly trained runners, however the attenuation lasted less than 24 hours and was not statistically significant at a higher running intensity (80% $\dot{V}O_2$ peak). The reliability of baseline EE measures at both 60% and 80% $\dot{V}O_2$ peak ($R^2 = 0.81$, $R^2 = 0.66$, respectively) suggest successful testing sessions and compare favorably with previous investigations (37).

Effect sizes were lower than expected based on pilot data specific to the protocol, and consequently a type II error may have occurred in regards to RE measured immediately post-PRT at 80% $\dot{V}O_2$ peak. We observed proportionally greater variance in RE at 80% $\dot{V}O_2$ peak as compared to the 60% segment, making statistical significance more difficult to achieve. However, this greater variability at higher running intensities does not appear to be a universal finding (14, 15, 31). When examining the similarity of RE results between conditions at the 24 hours post-treatment time point, it is clear that no other type II errors took place at any other time point.

Although this was not a mechanism-based investigation, it is assumed that RE was decreased immediately post-PRT due to induced skeletal muscle damage as well as decreases in muscle stiffness. Multiple investigations have identified both force production and muscle stiffness as primary constituents of RE (1, 22, 29, 34). High load RT results in a decrease of neural activation in exercised muscle (19) as well as a loss in maximal force production (41). Likewise, high volume plyometric training inhibits force and rate of force production, both functional markers of muscle damage (16). While it may have been ideal to include separate trials of plyometrics alone and RT alone in order to better distinguish their individual effects on RE, this was deemed logistically unrealistic for our highly trained subject pool due to the required rest (i.e., no running) periods.

Results related to the time course of RE impairment are consistent with those reported by Palmer and Sleivert (31) who used a subject pool with a similar aerobic capacity as well as a RT protocol with similar intensity and volume, albeit lacking in plyometric exercise and more upper body focused. That particular investigation found attenuations in RE at one and eight hours post-RT, but not at 24 hours (31). Generally, evidence is equivocal as to whether RT affects RE within 48 hours (9, 14, 15, 31, 36); however, available evidence suggests that performing aerobic training prior to RT is necessary to avoid acutely unfavorable outcomes in RE (14) or chronically unfavorable outcomes in running performance (11) when both training modes are completed on the same day. To our knowledge, no investigation reports a time course of RE impairment following a workout consisting solely of plyometric exercise. However, results from Drinkwater et al. suggest that any impairment of RE stemming from force or rate of force production impairment will last < 2 hours post-exercise which is consistent with the results from the present study (16).

Doma and Deakin (2013) reported a decrease in RE at 70% and 90% of ventilatory threshold (VT) the day after a RT and aerobically-oriented endurance workout (14). Even though it is population dependent, 70% and 90% of VT are marginally comparable intensities to 60 and 80% $\dot{V}O_2$ peak. Their subject pool was more diverse regarding frequency of aerobic training than the pool for the present study, but the reported $\dot{V}O_2$ max of 62.6 ± 6.0 ml/kg/min was very similar. Consequently, minor differences in routine RT practices of subjects may account for some of the discrepant results between the investigations. Subjects in the present study must have engaged in RT at least once in the three month period prior to testing; conversely, subjects for Doma and Deakin were restricted from lower body RT for two months prior to testing. While this may appear potentially trivial, Burt et al. provides evidence that even low intensity RT provides a repeated bout effect in regards to RE (9). The repeated bout effect refers to muscles' decreased susceptibility to damage following an initial injury or stress. The RT-induced repeated bout effect in relation to future attenuations in muscle damage lasts for up to six months (12); consequently, our subject pool may have been less susceptible to the muscle damaging effects of the PRT protocol even though subjects in the Doma and Deakin study would have acquired some degree of protection when undergoing baseline strength testing.

As RT may require a significant amount of glycogen use (24), the decrease in RER observed 24 hours after the PRT protocol was potentially due to reduced glycogen stores that would cause a shift away from glycolytic metabolism (20, 32) while running. This phenomenon was not present immediately post-exercise as lactate formed during the PRT protocol may have provided a readily available, carbohydrate-based source of aerobic energy (8) during the RE trial, ultimately raising RER to a comparable level of the CON trial. Although lactate was not measured, evidence suggests that blood lactate concentrations were likely increased as a result of the PRT protocol (17). The observed decrease in RER was only present in the 80% $\dot{V}O_2$ peak trial; this is not surprising as higher degrees of carbohydrate use by function of exercise intensity would be more susceptible to alterations.

Strength and conditioning professionals should appreciate that RE is just one component of running performance which rarely has been measured directly in relation to acute response to plyometrics or RT. It should be noted that Marcora and Bosio report a 4% decrease in 30-minute time trial running performance without alterations in RE after 100 jump landings from a 35 cm bench (25). However, Burt et al. (2015) displayed that the repeated bout effect in response to muscle damaging exercise (weighted squats) aids in the preservation of a 3 km running time trial performance (10).

In conclusion, RE returned to baseline levels within 24 hours after a high intensity, lower body PRT protocol in a highly trained subject pool. Future studies may benefit from investigating the timing effects of plyometric training on RE without the influence of RT, as well as including performance testing in addition to standard metabolic tests while employing PRT protocols that mimic typical collegiate or professional runner workouts.

PRACTICAL APPLICATIONS

Despite significant research evidence to the contrary, there remains concern in the running community that high intensity resistance or power-oriented training may harm endurance performance. Results from the present study should further alleviate concerns as the acute, deleterious effects of PRT are short-lived among a highly aerobically trained population. However, strength and conditioning coaches should be mindful that aerobic performance depends on multiple physiological factors beyond RE and employ caution when prescribing high intensity power or strength-oriented training within 48 hours of competition.

ACKNOWLEDGMENTS

None. We have no conflicts of interest to report.

REFERENCES

1. Arampatzis A, De Monte G, Karamanidis K, Morey-Klapsing G, Stafilidis S, and Bruggemann GP. Influence of the muscle-tendon unit's mechanical and morphological properties on running economy. *The Journal of experimental biology* 209: 3345-3357, 2006.
2. National Strength and Conditioning Association. *Essentials of Strength Training and Conditioning.* Champaign, IL, 2008.
3. Assumpção CO, Lima L, Oliveira F, Greco C, and Denadai B. Exercise-induced muscle damage and running economy in humans. *Scientific World Journal* Epub Feb 4, 2013.
4. Bassett DR, Jr. and Howley ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Medicine and science in sports and exercise* 32: 70-84, 2000.
5. Bellotti C, Calabria E, Capelli C, and Pogliaghi S. Determination of maximal lactate steady state in healthy adults: can NIRS help? *Medicine and science in sports and exercise* 45: 1208-1216, 2013.
6. Brandon LJ. Physiological factors associated with middle distance running performance. *Sports medicine* 19: 268-277, 1995.
7. Brisswalter J and Legros P. Daily stability in energy cost of running, respiratory parameters and stride rate among well-trained middle distance runners. *International journal of sports medicine* 15: 238-241, 1994.
8. Brooks GA. Cell-cell and intracellular lactate shuttles. *The Journal of physiology* 587: 5591-5600, 2009.
9. Burt D, Lamb K, Nicholas C, and Twist C. Effects of repeated bouts of squatting exercise on sub-maximal endurance running performance. *European journal of applied physiology* 113: 285-293, 2013.
10. Burt D, Lamb K, Nicholas C, and Twist C. Lower-volume muscle-damaging exercise protects against high-volume muscle-damaging exercise and the detrimental effects on endurance performance. *European journal of applied physiology* 115: 1523-1532, 2015.
11. Chtara M, Chamari K, Chaouachi M, Chaouachi A, Koubaa D, Feki Y, Millet GP, and Amri M. Effects of intra-session concurrent endurance and strength training sequence on aerobic performance and capacity. *British journal of sports medicine* 39: 555-560, 2005.

12. Clarkson PM and Hubal MJ. Exercise-induced muscle damage in humans. *American journal of physical medicine & rehabilitation / Association of Academic Physiatrists* 81: S52-69, 2002.
13. Daniels JT. A physiologist's view of running economy. *Medicine and science in sports and exercise* 17: 332-338, 1985.
14. Doma K and Deakin GB. The effects of strength training and endurance training order on running economy and performance. *Applied physiology, nutrition, and metabolism = Physiologie appliquee, nutrition et metabolisme* 38: 651-656, 2013.
15. Doma K and Deakin GB. The acute effects intensity and volume of strength training on running performance. *European journal of sport science* 14: 107-115, 2014.
16. Drinkwater EJ, Lane T, and Cannon J. Effect of an acute bout of plyometric exercise on neuromuscular fatigue and recovery in recreational athletes. *Journal of strength and conditioning research / National Strength & Conditioning Association* 23: 1181-1186, 2009.
17. Essen-Gustavsson B and Tesch PA. Glycogen and triglyceride utilization in relation to muscle metabolic characteristics in men performing heavy-resistance exercise. *European journal of applied physiology and occupational physiology* 61: 5-10, 1990.
18. Favero TG, Zable AC, Colter D, and Abramson JJ. Lactate inhibits Ca(2+) -activated Ca(2+)-channel activity from skeletal muscle sarcoplasmic reticulum. *Journal of applied physiology* 82: 447-452, 1997.
19. Hakkinen K. Neuromuscular fatigue and recovery in male and female athletes during heavy resistance exercise. *International journal of sports medicine* 14: 53-59, 1993.
20. Holloszy JO, Kohrt WM, and Hansen PA. The regulation of carbohydrate and fat metabolism during and after exercise. *Frontiers in bioscience : a journal and virtual library* 3: D1011-1027, 1998.
21. Jackson AS and Pollock ML. Practical assessment of body composition. *Physician and Sports Medicine* 13: 76-90, 1985.
22. Johnson R, Quinn T, Kertzer R, and Vroman N. Strength training in female distance runners: impact on running economy. *Journal of strength and conditioning research / National Strength & Conditioning Association* 11: 224-229, 1997.
23. Lusk G. *The Elements of the Science of Nutrition.* Philadelphia, PA: W.B. Sauders Company, 1928.
24. MacDougall JD, Ray S, Sale DG, McCartney N, Lee P, and Garner S. Muscle substrate utilization and lactate production. *Canadian journal of applied physiology = Revue canadienne de physiologie appliquee* 24: 209-215, 1999.
25. Marcora SM and Bosio A. Effect of exercise-induced muscle damage on endurance running performance in humans. *Scandinavian journal of medicine & science in sports* 17: 662-671, 2007.
26. Millet GP, Jaouen B, Borrani F, and Candau R. Effects of concurrent endurance and strength training on running economy and VO(2) kinetics. *Medicine and science in sports and exercise* 34: 1351-1359, 2002.
27. Moran M and Greer B. Influence of midsole 'actuator lugs' on running economy in trained distance runners. *Footwear Science* 5: 91-99, 2013.
28. Morgan DW, Martin PE, and Krahenbuhl GS. Factors affecting running economy. *Sports medicine* 7: 310-330, 1989.
29. Nummela AT, Paavolainen LM, Sharwood KA, Lambert MI, Noakes TD, and Rusko HK. Neuromuscular factors determining 5 km running performance and running economy in well-trained athletes. *European journal of applied physiology* 97: 1-8, 2006.
30. Paavolainen L, Hakkinen K, Hamalainen I, Nummela A, and Rusko H. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *Journal of applied physiology* 86: 1527-1533, 1999.

31. Palmer CD and Sleivert GG. Running economy is impaired following a single bout of resistance exercise. *Journal of science and medicine in sport / Sports Medicine Australia* 4: 447-459, 2001.
32. Ravussin E, Pahud P, Dorner A, Arnaud MJ, and Jequier E. Substrate utilization during prolonged exercise preceded by ingestion of 13C-glucose in glycogen depleted and control subjects. *Pflugers Archiv : European journal of physiology* 382: 197-202, 1979.
33. Reeves MM, Davies PS, Bauer J, and Battistutta D. Reducing the time period of steady state does not affect the accuracy of energy expenditure measurements by indirect calorimetry. *Journal of applied physiology* 97: 130-134, 2004.
34. Saunders PU, Pyne DB, Telford RD, and Hawley JA. Factors affecting running economy in trained distance runners. *Sports medicine* 34: 465-485, 2004.
35. Saunders PU, Telford RD, Pyne DB, Peltola EM, Cunningham RB, Gore CJ, and Hawley JA. Short-term plyometric training improves running economy in highly trained middle and long distance runners. *Journal of strength and conditioning research / National Strength & Conditioning Association* 20: 947-954, 2006.
36. Scott KE, Rozenek R, Russo AC, Crussemeyer JA, and Lacourse MG. Effects of delayed onset muscle soreness on selected physiological responses to submaximal running. *Journal of strength and conditioning research / National Strength & Conditioning Association* 17: 652-658, 2003.
37. Shaw AJ, Ingham SA, and Folland JP. The valid measurement of running economy in runners. *Medicine and science in sports and exercise* 46: 1968-1973, 2014.
38. Storen O, Helgerud J, Stoa EM, and Hoff J. Maximal strength training improves running economy in distance runners. *Medicine and science in sports and exercise* 40: 1087-1092, 2008.
39. Stringer W, Wasserman K, Casaburi R, Porszasz J, Maehara K, and French W. Lactic acidosis as a facilitator of oxyhemoglobin dissociation during exercise. *Journal of applied physiology* 76: 1462-1467, 1994.
40. Turner AM, Owings M, and Schwane JA. Improvement in running economy after 6 weeks of plyometric training. *Journal of strength and conditioning research / National Strength & Conditioning Association* 17: 60-67, 2003.
41. Warren GL, Lowe DA, and Armstrong RB. Measurement tools used in the study of eccentric contraction-induced injury. *Sports medicine* 27: 43-59, 1999.

FIGURE LEGENDS

Figure 1. Study design diagram. 1 RM = one-repetition maximum; RE = 12 minute running economy test; PRT = plyometric and resistance training protocol; CON = control protocol.

Table 1. Mean ± *SD* of Subject Characteristics (*N* = 8)

Age (years)	21 ± 1
Height (cm)	175.6 ± 6.1
Body Mass (kg)	63.9 ± 8.5
BMI (kg/m^2)	20.7 ± 2.6
Body Fat (%)	10.5 ± 3.4
VO_2 peak (ml/kg/min)	62.5 ± 7.8
1RM Squat (kg)	79.0 ± 14.9
1RM RDL (kg)	63.4 ± 20.7
1RM Lunge (kg)	52.6 ± 9.2

BMI = body mass index; VO_2 = oxygen consumption; 1RM = one-repetition maximum; RDL = Romanian deadlift.

Table 2. Mean ± *SD* of Metabolic Measurements for 60% VO_2 Peak Trial ($N = 8$)

	Pre		*Post*		*24 Hr. Post*	
	PRT	*CON*	*PRT*	*CON*	*PRT*	*CON*
VO_2 (ml/kg/min)	35.9 ± 3.8	36.3 ± 3.8	37.1 ± 4.2*	35.5 ± 4.0	35.8 ± 4.1	36.1 ± 4.5
EE (kcal/min)	11.1 ± 1.1	11.3 ± 1.3	11.4 ± 1.3*	11.1 ± 1.4	11.0 ± 1.3	11.3 ± 1.6
RER	0.86 ± 0.0	0.87 ± 0.0	0.85 ± 0.0	0.87 ± 0.0	0.86 ± 0.0	0.88 ± 0.0

* Statistically significantly different than CON ($p < 0.05$)

VO_2 = oxygen consumption, EE = energy expenditure, RER = respiratory exchange ratio,
PRT = plyometric and resistance training trial, CON = control trial

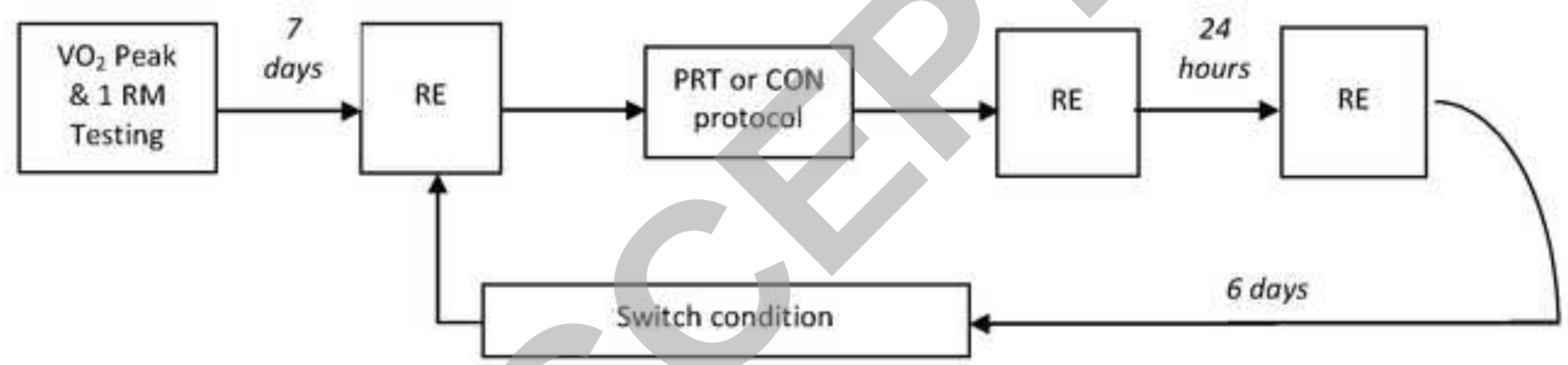
Table 3. Mean ± *SD* of Metabolic Measurements for 80% VO_2 Peak Trial ($N = 8$)

	Pre		*Post*		*24 Hr. Post*	
	PRT	*CON*	*PRT*	*CON*	*PRT*	*CON*
VO_2 (ml/kg/min)	51.0 ± 7.1	50.2 ± 7.0	51.9 ± 6.5	50.4 ± 6.9	50.5 ± 6.4	50.4 ± 7.7
EE (kcal/min)	16.0 ± 2.5	16.0 ± 2.4	16.4 ± 2.3	15.9 ± 2.3	15.9 ± 2.2	16.1 ± 2.6
RER	0.93 ± 0.0	0.95 ± 0.0	0.94 ± 0.0	0.93 ± 0.0	0.93 ± 0.0*	0.96 ± 0.0

* Statistically significantly different than CON ($p < 0.05$)

VO_2 = oxygen consumption, EE = energy expenditure, RER = respiratory exchange ratio, PRT = plyometric and resistance training trial, CON = control trial

Figure


VO$_2$ Peak & 1 RM Testing
7 days
RE
PRT or CON protocol
RE
24 hours
RE
6 days
Switch condition