Effect of Plyometric vs. Dynamic Weight Training on the Energy Cost of Running

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Abstract

Berryman, N, Maurel, D, and Bosquet, L. Effect of plyometric vs. dynamic weight training on the energy cost of running. *J Strength Cond Res* 24(7): 1818–1825, 2010—The purpose of this study is to compare the effects of 2 strength training methods on the energy cost of running (C_r). Thirty-five moderately to well-trained male endurance runners were randomly assigned to either a control group (C) or 2 intervention groups. All groups performed the same endurance-training program during an 8-week period. Intervention groups added a weekly strength training session designed to improve neuromuscular qualities. Sessions were matched for volume and intensity using either plyometric training (PT) or purely concentric contractions with added weight (dynamic weight training [DWT]). We found an interaction between time and group ($p < 0.05$) and an effect of time ($p < 0.01$) for C_r. Plyometric training induced a larger decrease of C_r (218 ± 16 to 203 ± 13 ml·kg^{-1}·km^{-1}) than DWT (207 ± 15 to 199 ± 12 ml·kg^{-1}·km^{-1}), whereas it remained unchanged in C. Pre–post changes in C_r were correlated with initial C_r ($r = -0.57$, $p < 0.05$). Peak vertical jump height (VJH_{peak}) increased significantly ($p < 0.01$) for both experimental groups (DWT = 33.4 ± 6.2 to 34.9 ± 6.1 cm, PT = 33.3 ± 4.0 to 35.3 ± 3.6 cm) but not for C. All groups showed improvements ($p < 0.05$) in $Perf_{3000}$ (C = 711 ± 107 to 690 ± 109 seconds, DWT = 755 ± 87 to 724 ± 77 seconds, PT = 748 ± 81 to 712 ± 76 seconds). Plyometric training were more effective than DWT in improving C_r in moderately to well-trained male endurance runners showing that athletes and coaches should include explosive strength training in their practices with a particular attention on plyometric exercises. Future research is needed to establish the origin of this adaptation.

Key Words concurrent training, half squat, drop jump, running performance

Introduction

Successful running performance in long duration events is directly influenced by maximal oxygen uptake ($\dot{V}O_2max$), fractional use of $\dot{V}O_2max$ (End), and the energy cost of running (C_r) (10). Although we have been aware of its importance since the 1970s, the state of knowledge about C_r is low compared to our understanding of $\dot{V}O_2max$ or End (10,13). C_r is the O_2 equivalent of the energy required to run through a given distance at a submaximal speed (32). It is particularly relevant to predict performance in individuals with similar $\dot{V}O_2max$ (9) and has been acknowledged as one of the multiple determinants of East African runners' domination in international competitions (21). C_r depends on a complex interplay of factors including training, environment, physiology, biomechanics, anthropometry, and training (32). Recent research suggests that strength training is one of the most powerful interventions for improving C_r (17,28,34,36,37) However, because muscular hypertrophy has been shown to interfere with some peripheral aerobic adaptations, (5,23) it has been suggested that implementations should use strength training methods that emphasize on neural adaptations (11).

Plyometric and dynamic weight training (PT and DWT) fulfill this requirement (14,20,40). Plyometric training involves an eccentric contraction immediately followed by a concentric contraction to allow the muscle to store and recoil elastic energy (6,24,38). Jumps and rebounds are typically used to induce this muscle strech shortening cycle. Dynamic weight training involves concentric contractions leading to the maximal power output (40). It generally consists in moving relatively light loads (between 30 and 50% of 1 repetition maximum) as fast as possible (40).

The effectiveness of plyometric and DWT (either alone or in combination) to decrease C_r has been highlighted in several convergent reports (28,35,37). In a recent study (35), 8 moderately trained endurance runners improved C_r after

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they completed a 6-week program of high volume–low intensity plyometric training in concomitance with their usual endurance training. In another study (37) in which the authors implemented a comparable plyometric training program, they also found a moderate decrease in C_r. Other authors (28) replaced 32% of the usual endurance training volume of 12 elite crosscountry runners by an explosive strength training program involving both plyometric and DWT. They reported a large decrease in C_r, thus confirming the effectiveness of these methods to improve running efficiency. However, to the best of our knowledge, no attempt has been made to determine whether 1 of these 2 methods was more appropriate in improving C_r. Physiological and practical applications of this issue are important. They could provide evidence-based data to the coach that may help in the optimization of the strength training of endurance athletes and experimental data to the scientist that may contribute to our understanding of the mechanisms underpinning improvement in C_r.

Therefore, the purpose of this study was to compare the effectiveness of 2 strength training methods matched for volume and intensity to improve C_r in male endurance athletes. Because it allows the use of series and parallel elastic components and has therefore the potential for improving the ability of the muscle tendon unit to store and recoil elastic energy, we hypothesized that plyometric training would result in a greater decrease in C_r than DWT.

Methods

Experimental Approach to the Problem

After a thorough briefing and medical screening, all participants signed a written statement of informed consent. Once included, they first completed a maximal continuous graded exercise test (session 1), followed by a force–velocity test (session 2), a countermovement jump test, and a performance test (session 3). All tests were separated by at least 48 hours and were performed in a 7-day period, before and after an 8-week training period. To avoid any residual fatigue induced by recent training, participants were asked to refrain from strenuous exercise the day before the tests. They were also asked to arrive fully hydrated to the laboratory, at least 3 hours after their last meal. No attempt was made to control the content of this meal. After initial testing, participants were randomly assigned to the DWT group, PT group, and the control group (C). The groups were matched for age and peak oxygen consumption. There were no initial differences in other dependent variables between groups.

Subjects

Thirty-five moderately to well-trained male endurance runners with no history of strength training participated in this study. They were competing at a provincial-standard level (3–7 training sessions per week) at distances between 5,000 and 42,195 m. Their age, stature, body mass, body mass index, and sum of skin folds (triceps, biceps, subscapular, and suprailiac) are reported in Table 1. The protocol was reviewed and approved by the Research Ethics Board in Health Sciences of the University of Montreal, Canada.

Procedures

Exercise Testing. Maximal continuous graded exercise test: This test was performed on a motorized treadmill (Quinton, Bothell, WA, USA), which was calibrated at 8 and 16 $km\cdot h^{-1}$ (gradient = 0) before each session with an "in-house" system using an optical sensor connected to an acquisition card. Initial speed was set at 12 $km\cdot h^{-1}$ for 6 minutes, to determine the energy cost of running, and increased by 0.5 $km\cdot h^{-1}$ every minute until exhaustion. The grade was set at zero throughout the test. The speed of the last completed stage was considered as the peak treadmill speed (PTS). Oxygen uptake ($\dot{V}O_2$) was determined continuously on a 15-second basis using an automated cardiopulmonary exercise system (Moxus, AEI Technologies, Naperville, IL, USA). Gas analyzers (S3A and CD3A, AEI Technologies, Naperville, IL, USA) were calibrated before each test, using a gas mixture of known concentration (15% O_2 and 5% CO_2) and ambient air. Their accuracy was ±0.003% for oxygen and ±0.02% for

Table 1. Physical characteristics of the participants during the experimental protocol.*†

	DWT (n = 12)		PT (n = 11)		C (n = 5)	
Variables	Pre	Post	Pre	Post	Pre	Post
Age (y)	31 ± 7	31 ± 7	29 ± 8	29 ± 8	29 ± 11	29 ± 11
Stature (cm)	176 ± 7	176 ± 7	178 ± 6	178 ± 6	180 ± 6	180 ± 6
Body mass (kg)	76.3 ± 8.0	76.2 ± 8.6	74.6 ± 7.6	74.6 ± 6.9	75.9 ± 5.0	75.8 ± 5.5
Body mass index ($kg\cdot m^{-2}$)	24.6 ± 2.3	24.6 ± 2.2	23.7 ± 3.0	23.7 ± 2.8	23.6 ± 2.6	23.6 ± 2.9
Sum of 4 skin folds (cm)	38.6 ± 12.6	39.6 ± 13.3	39.0 ± 10.0	37.6 ± 10.4	33.7 ± 12.2	33.7 ± 12.4

*DWT = dynamic weight training; PT = plyometric training; C = control.
†Values are given as mean ± *SD.*

TABLE 2. Basic endurance training program.*

	Session #1			Session #2			Session #3	
Week	Volume (m)	Intensity (% PTS)	Rest (s)	Volume (min)	Intensity (% PTS)	Rest (s)	Volume (min)	Intensity (% PTS)
1	10 × 200	105	40	4 × 5	80	3	40	70
2	10 × 300	102	60	5 × 5	80	3	45	70
3	10 × 400	100	90	6 × 5	80	3	50	70
4	6 × 200	105	40	3 × 5	80	3	30	70
5	10 × 400	100	90	2 × 10	80	3	40	70
6	8 × 600	98	120	3 × 10	80	3	50	70
7	6 × 800	96	150	2 × 15	80	3	60	70
8	6 × 200	105	90	30	70		30	70

*It was not required to respect the order of the sessions as is presented in this table.

carbon dioxide (data provided by the manufacturer). The turbine was calibrated before each test using a motorized syringe (Vacu-Med, Ventura, CA, USA) with an accuracy of ±1%.(18) The tidal volume was set at 3l and the stroke rate at 40 cycles per minute. Mean $\dot{V}O_2$ over the last 2 minutes of the initial 6-minute bout was divided by speed to calculate the energy cost of running (C_r, in ml·kg^{-1}·km^{-1}). The highest $\dot{V}O_2$ over a 15-second period during the test was considered as peak oxygen consumption ($\dot{V}O_2$peak, in ml·kg^{-1}·min^{-1}).

Force–velocity test: This test was performed on a guided squat rack allowing only vertical movements (Atlantis, Laval, Quebec, Canada). When cued, the participant moved from the standing position into a semisquat position (90° knee flexion) and had to stay motionless for 4 seconds (39) before moving the load as fast as possible. Two consecutive trials were performed per load, with the best reading recorded for further analyses. Three minutes of passive recovery was given between each load. Maximal average velocity and power were recorded by linking a shuttle to the end part of the bar locked to an infrared sensor (Musclelab, Ergotest, Norway). The accuracy of this electronic device reached the 10-microsecond time resolution with an optical transducer interruption each 3 mm of displacement (2). Average velocity and power were calculated through the whole range of motion used to perform a complete repetition (from 90° knee flexion to the full extension). Power–load curve was plotted during the test. The initial load was 10 kg and was increased by 10 kg until the flattening of the Power–Load curve and by increments of 5 kg afterward. The test was completed when power decreased during at least 2 consecutive loads. The highest power was considered as peak power (P_{peak}, in W).

Countermovement jump test: This test was performed in the laboratory. When cued, the participant made a countermovement before jumping as high as possible. The hands had to be placed on the hips throughout the entire jump. No specific instruction was given regarding the depth or speed of the countermovement. Three trials separated by 1 minute of passive recovery were performed. The best one was recorded for further analyses. Vertical jump height was calculated from flight time using basic kinematic equations (22). Flight time was recorded with an optical system consisting of 2 bars placed opposite to each other and connected to a PC via the serial port (Optojump, Microgate, Bozano, Italy). This system transmits an infrared light 1–2 mm above the floor. When the light is interrupted by the feet, the units trigger a timer with a precision of 1 microsecond. The highest height was considered as peak vertical jump height (VJH_{peak}, in cm).

Performance test: This test was performed on a 200-m indoor track and consisted in an individual 3,000-m run. Participants were instructed to cover the distance as fast as possible and encouraged to maintain an even pace throughout the run in order to produce the best performance. Time was measured to the nearest second and considered as the performance criterion ($Perf_{3,000}$, in seconds). Mean

TABLE 3. Strength training program.*

Week	Sets	Repetitions	Rest
1	3	8	3
2	4	8	3
3	5	8	3
4	Test to adjust training intensity		
5	4	8	3
6	5	8	3
7	6	8	3
8	3	8	3

*Training intensities are given in the text.

velocity over the 3,000 m was calculated and divided by PTS to estimate aerobic endurance (End, in % PTS) (3).

Training Interventions

Endurance Training. All participants (DWT, PT, and C) followed the same basic endurance-training program that was typical to what they were already doing. It involved 2 high-intensity interval training sessions and 1 low-intensity continuous training session per week. The content of these training sessions is described in Table 2.

Strength Training. Participants of the control group did not train for strength, whereas participants of DWT and PT groups performed 1 strength training session per week. The strength training program was designed to improve maximal power, defined as the ability to produce a high amount of force over a very short period of time (30). Training details relative to the number of sets and repetitions are given in Table 3. Rapid improvements were expected because participants had no experience in this kind of training. Therefore, the fourth training session was dedicated to the adjustment of training intensities by the mean of specific tests.

Participants of the DWT group were required to perform purely concentric semisquats on a guided squat rack allowing only vertical movements (Atlantis, Laval, Quebec, Canada) and to move the load as fast as possible. This load was determined individually; it corresponded to the load allowing the attainment of P_{peak} during the force–velocity test. Average power through the whole range of motion was measured with an infrared sensor (Musclelab, Ergotest, Norway; see *Force–velocity test* for a more complete description). A trial was counted only if power was at least 95% of P_{peak} measured during the force–velocity test; otherwise it had to be recommenced. Feedback about power and validity of the trial was given at after each repetition.

Participants of the PT group were required to perform drop jumps from 20, 40, or 60-cm jump boxes. Briefly, a drop jump consists in stepping down from a given height and bouncing as high as possible. The hands have to be placed on the hips throughout the entire jump. In our study, no specific instruction was given regarding the depth or speed of the countermovement. The height of the jump box was determined individually; it corresponded to the height that allowed the participant to reach the highest vertical jump height (supposedly the highest power). Vertical jump height was measured with an optical system (Optojump, Microgate; see Countermovement Jump Test for a more complete description). A trial was counted only if the vertical jump height was at least 95% of the maximal vertical jump height reached during the first or the fourth training session; otherwise, it had to be recommenced. Feedback about vertical jump height and validity of the trial was given after each repetition.

TABLE 4. Physiological and neuromuscular results in the experimental and control groups.*†

Variables	DWT (n = 12) PRE	DWT POST	DWT ES	PT (n = 11) PRE	PT POST	PT ES	C (n = 5) PRE	C POST	C ES
$\dot{V}o_2peak$ (ml·kg^{-1}·min^{-1})	57.5 ± 6.7	56.1 ± 6.7	0.20	57.5 ± 6.5	57.3 ± 5.5	0.03	55.7 ± 8.2	55.3 ± 8.9	0.04
PTS (km·h^{-1})	16.6 ± 1.5	17.3 ± 1.6‡	0.43	16.6 ± 1.3	17.3 ± 1.3‡	0.49	17.3 ± 2.0	17.5 ± 2.4	0.09
End (% PTS)	87.1 ± 4.7	87.1 ± 2.8	0.00	87.6 ± 3.8	88.6 ± 3.9	0.25	89.1 ± 4.7	91.1 ± 3.5	0.47
Cr (ml·kg^{-1}·km^{-1})	207 ± 15	199 ± 12‡	0.62	218 ± 16	203 ± 13‡§	1.01	199 ± 18	199 ± 20	0.00
Cr (ml·kg$^{-0.75}$·km^{-1})	612 ± 45	587 ± 35‡	0.63	641 ± 49	596 ± 43‡§	0.96	588 ± 53	588 ± 60	0.00
Ppeak (W)	1,147 ± 180	1,324 ± 181‡§	0.98	1,174 ± 138	1,214 ± 190‡	0.24	1,206 ± 165	1,201 ± 123	0.04
VJHpeak (cm)	33.4 ± 6.2	34.9 ± 6.1‡	0.25	33.3 ± 4.0	35.3 ± 3.6‡	0.52	34.2 ± 3.6	35.2 ± 4.2	0.26
$Perf_{3,000}$ (s)	755 ± 87	724 ± 77‖	0.37	748 ± 81	712 ± 76‖	0.46	711 ± 107	690 ± 109‖	0.20

*DWT = dynamic weight training; PT = plyometric training; C = control; PRE = pretraining; POST = posttraining; ES = effect size.
†Values are given as mean ± *SD*.
§Interaction time × group ($p < 0.05$).
‡Different from PRE ($p < 0.01$).
‖Different from PRE ($p < 0.05$).

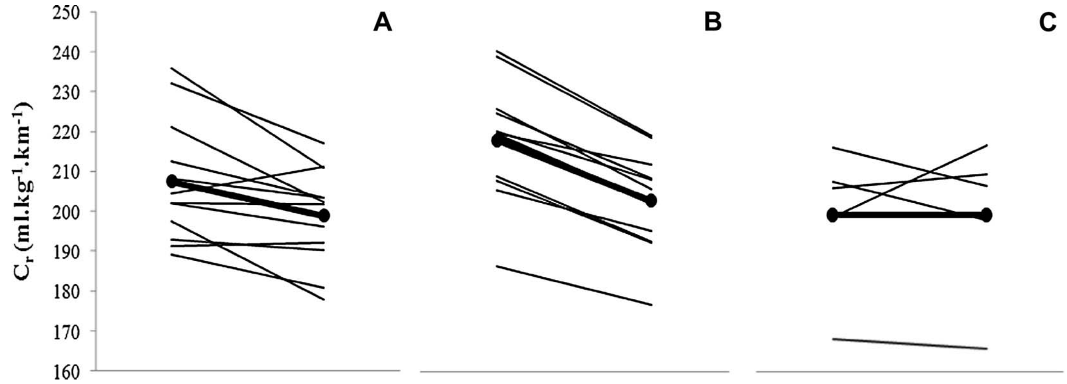

Figure 1. Individual changes in C_r from pre to posttraining for the 3 different experimental conditions. A) dynamic weight training ($n = 12$); B) plyometric training ($n = 11$); and C) control group ($n = 5$). The thick line represents group average.

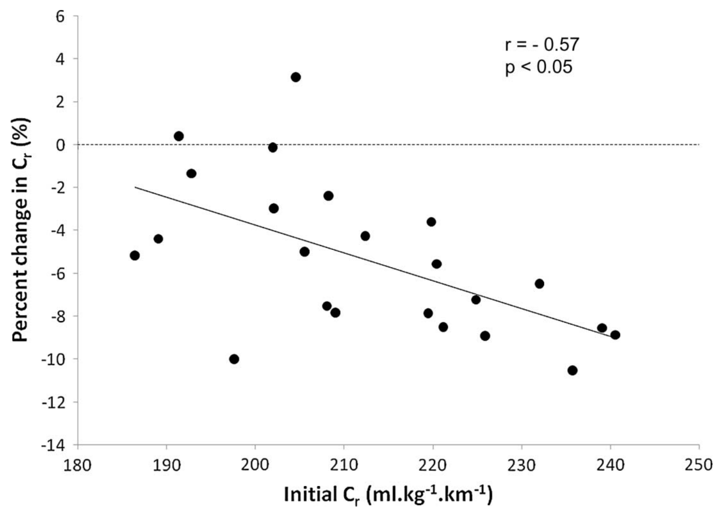

Figure 2. Correlation between the initial level in C_r and the percentage of changes from pre to posttraining for the subjects from the experimental groups ($n = 23$).

Statistical Analyses

Standard statistical methods were used for the calculation of means and *SD*s. Normal Gaussian distribution of the data was verified by the Shapiro–Wilk test and homoscedascticity by a modified Levene Test. All variables met these underlying hypotheses. A 2-way analysis of variance (ANOVA) (Time $\times$ Group) with repeated measures on the Time factor was performed. Multiple comparisons were made with the Bonferroni post hoc test. The magnitude of the difference was assessed by the effect size (ES), calculated according to the following equation:

$$\mathrm{ES} = \frac{M_2 - M_1}{SD_{\mathrm{pooled}}},$$

where ES is the effect size, M_1 and M_2 are the mean of the first and the second trial and SD_{pooled} is the pooled *SD*, calculated as follows:

$$SD_{\mathrm{pooled}} = \sqrt{\frac{(S_1^2 \times (n_1 - 1)) + (S_2^2 \times (n_2 - 1))}{(n_1 + n_2 - 2)}},$$

where ${S_1}^2$ and ${S_2}^2$ are the variance of the first and the second trials, and n is the number of participants. The magnitude of the difference was considered either small ($0.2 < \mathrm{ES} \leq 0.5$), moderate ($0.5 < \mathrm{ES} \leq 0.8$), or large ($\mathrm{ES} > 0.8$) (8). Pearson product moment correlation was used to evaluate the association between relevant parameters. The significance level was set at $p \leq 0.05$. All calculations were made with Statistica 6.0 (Statsoft, Tulsa, USA).

Results

Seven participants did not complete the 8-week training program and were withdrawn from the study. The main reasons were illness ($n = 1$), lack of motivation ($n = 2$), or injury ($n = 4$). It is worth noting that none of the injuries occurred during a strength training session. We deplored an ankle sprain during hiking ($n = 1$) and minor muscular tears during a graded exercise test ($n = 1$) or during a recreational activity ($n = 2$). Final sample sizes were $n = 12$ in DWT, $n = 11$ in PT, and $n = 5$ in C. These participants completed 97% (DWT), 99% (PT), and 100% (C) of the scheduled sessions, which reflects a very high training compliance.

There were no initial differences in dependent variables between groups. Body mass, body mass index, and the sum of skin folds did not change after the 8-week training intervention (Table 1), nor did $\dot{V}O_2$peak or End (Table 4). The 2-way ANOVA revealed an interaction between time and group ($p < 0.05$) and an effect of time for C_r ($p < 0.01$, Table 4), whatever the power attributed to body mass (kg^{-1} or $kg^{-0.75}$). Post hoc analysis allowed us to identify a moderate decrease in DWT (ES = 0.62, $p < 0.01$) and a large decrease in PT (ES = 1.01, $p < 0.01$). There was no improvement in C (ES = 0.00, NS). Individual results are shown in Figure 1. We also found an interaction between time and group ($p < 0.05$) and an effect of time ($p < 0.01$) for P_{peak} (Table 4). The addition of a weekly strength training session induced a large increase of P_{peak} in DWT (ES = 0.98, $p < 0.01$) and a small increase in PT (ES = 0.24, $p < 0.01$). No differences were found in C (ES = 0.04, NS). We found an effect of time for VJH_{peak} ($p < 0.01$). Both experimental groups improved VJH_{peak} (PT: ES = 0.52, $p < 0.01$ − DWT: ES = 0.25, $p < 0.01$). No differences were found for C (ES = 0.26, NS). $Perf_{3000}$ increased moderately in PT (ES = 0.46, $p < 0.05$) and in DWT (ES = 0.37, $p < 0.05$). Improvements in $Perf_{3000}$ were small for C (ES = 0.20, $p < 0.05$). No correlations were found, by the exception of an association between initial C_r and the percent change after the training intervention in experimental groups ($r = -0.57$, $p < 0.05$; Figure 2).

Discussion

The aim of this study was to compare the effectiveness of 2 strength training methods matched for volume and intensity to improve C_r in male endurance athletes. We hypothesized that plyometric training would result in a greater decrease in C_r because of an improved storage-recoil capacity of elastic energy. Our results partly confirmed this hypothesis. Participants of PT displayed a greater decrease in C_r than their DWT's counterparts (7% vs. 4%). It has to be mentioned that results from a recent article show that changes in C_r greater than 2.4% can be attributable to a training intervention rather than a testing error or day-to day variations (33). However, we failed to find any relationship with the capacity to store and recoil elastic energy as no correlations were found between changes in VJH_{peak} and changes in C_r.

It has been shown that $\dot{V}O_2$ does not increase in proportion to body mass during both submaximal and maximal intensity running (1). To avoid misinterpretations when comparing individuals with different body masses, such as children and normal or overweight adults, it is often recommended to express $\dot{V}O_2$ relative to the body mass raised to the power of 0.75 (1,16). In addition to improve the validity of comparisons, this allometric scaling has been reported to decrease interindividual variability (16), thus increasing statistical power. We made a sensitivity analysis between C_r expressed in $ml \cdot kg^{-0.75} \cdot m^{-1}$ or in $ml \cdot kg^{-1} \cdot m^{-1}$ and found no reason to use one approach instead of the other one. Because body mass was homogeneous (as measured by a modified Levenne Test) and not different between DWT, PT, and C, we finally opted for the classical approach (i.e., body mass raised to the power of 1).

A recent research (35) examined the effect of plyometric training on C_r. Eight moderately to well-trained male endurance runners added 2 sessions of high volume–low intensity plyometric training per week during 6 weeks to their usual endurance training. The authors found a moderate decrease in C_r ($p < 0.05$, ES = 0.46), whereas both End (as measured by lactate threshold) and $\dot{V}O_2$peak remained unchanged. Other authors (34,37) reported similar amplitudes of improvement after a 6- to 9-week high volume–low intensity plyometric training period in moderately to well-trained endurance athletes ($p < 0.05$, ES = 0.28–0.30). In contrast to these reports, participants of the present study performed a low volume–high intensity plyometric training. Our results confirm the positive effect of such training on C_r but with a much greater amplitude of improvement ($p < 0.01$, ES = 1.01). It should be noted that these gains were obtained with only 1 session per week. It is far less than current recommendations (30,31) or practices (34,35,37). A recent meta-analysis examining the effectiveness of plyometric training for improving vertical jump height reported an overall ES of 0.84 (38). The ES of the PT group, which was 1.01, underscore the undoubted efficiency of the method we used in this study that relied more on training intensity than training volume.

We were not able to find a concurrent strength and endurance training study that used the same weight training protocol than ours. In a recent study (26), 7 well- to highly trained triathletes added 2 sessions of low-volume, low-velocity, and high-intensity strength training per week during 14 weeks to their usual endurance training. They reported a large decrease in C_r ($p < 0.05$, ES = 1.10), whereas End (as measured by the second ventilator threshold) and $\dot{V}O_2$peak remained the same. These results were confirmed very recently (36). The authors found a large decrease in C_r ($p < 0.05$, ES = 1.03) in 8 moderately to well-trained endurance athletes after a high intensity, low velocity, and low volume strength training program 3 $d \cdot wk^{-1}$ during an 8-week period. In our study, participants of DWT performed a low-volume, high-velocity, and moderate-intensity strength training that allowed reaching at least 95% of maximal power. This intervention resulted in a moderate decrease in C_r ($p < 0.01$, ES = 0.63). This amplitude of improvement was less than results previously published (26,36). Several factors may have contributed to this difference. Current guidelines recommend 2–3 sessions per week to improve maximal strength (30,31). In this study, participants of experimental groups added only 1 session per week to their endurance training. It is possible that the overall training load was not sufficient to stress adequately adaptation processes in DWT. However, the large increase in P_{peak} ($p < 0.01$, ES = 0.98) we observed in this group, which was comparable with the gains reported in strength alone training studies ($p < 0.01$, ES = 1.03) (40), does not support this contention. Another possible explanation is that concentric maximal power per se is not a major determinant of C_r. If such an association existed, the corollary for the higher increase of P_{peak} we found in DWT should have been a higher decrease in C_r. The inverse was true, because we observed an interaction that favors PT and found no association between changes in P_{peak} and changes in C_r.

Because they used the same movement and were matched for training volume and intensity, the main difference between DWT and PT was the type of muscular contraction. Although DWT was purely concentric, PT allowed the use of series and parallel elastic components and therefore had the potential for improving the ability of the muscle–tendon unit to store and recoil elastic energy. However, we were not able to find any association between changes in VJH_{peak} and changes in C_r, nor any interaction between experimental groups regarding jump performance. Adaptations regarding the ability to use elastic energy and to develop more power probably differed between PT and DWT (38), but both contributed to the increased VJH_{peak}. Therefore, it appears that the countermovement jump test was not sensitive enough in itself to underline specific improvements in the ability to store and recoil elastic energy. Another possible explanation could be related to the important number of factors influencing C_r. It is possible that improvements in power and in the ability to use elastic energy are not the only determinants that contributed to a decrease in C_r. Indeed, some authors reported that changes in muscle stiffness and mechanical factors can influence C_r (15,25,27,32). A limit of this study is therefore the lack of a sensitive measure of these neuromuscular determinants.

The inverse relationship we found between initial C_r and percent change in C_r suggests that already efficient runners did not take the same advantage from a strength training program than less efficient ones. Either their adaptation capacity was at its maximum or more probably the training methods we used in this study were not adequate to stress it at a higher level. This issue has already been addressed (12). These authors assigned 12 novice and 14 varsity female rowers to either a low intensity–high repetition (H-rep) or a high intensity–low repetition (H-load) strength training group. Performance at a 2,000-m rowing ergometer test was recorded before and after an 8-week combined strength and endurance-training period. Interestingly, the authors reported that varsity rowers who performed H-load training demonstrated greater improvements in performance compared with those who performed H-rep training. Inversely, H-rep training was more effective than H-load training in novice participants. Our results and these results (12) concur with the hypothesis that the effectiveness of strength training to improve C_r or performance is dependent on both training status and the characteristics of strength training load.

The ultimate objective with athletic training is to improve performance. In this study, runners from the experimental groups and from the control group showed significant gains in $Perf_{3,000}$. Although these results were expected for both PT and DWT, improvements for C are surprising considering that no performance determinants were modified. It should be kept in mind however that the variability of $\dot{V}O_2max$ END and C_r explains roughly 70% of the variability in marathon performance (10). This means that other factors are involved that were not measured in this study, such as psychological variables (29) and the use of other metabolic (anaerobic) pathways (4,28). Finally, although we found no interaction between groups, their respective ES (0.46, 0.37, and 0.20) suggests that the gains were higher in experimental groups and could have been significant with more statistical power.

Practical Applications

It has been shown that C_r can predict performance for middle and long distance runners with similar $\dot{V}O_2max$ values. C_r is influenced by a number of factors including strength training and neuromuscular adaptations. The purpose of this study was to compare the effectiveness of 2 strength training methods matched for volume and intensity to improve C_r in male endurance athletes. Our results confirm that athletes and coaches should include in their practices a precise assessment of C_r to plan an optimal training program. Although it is well known that strength training represents an important intervention to reduce the prevalence of injury (7,19), our results show that explosive strength training and more particularly PT is, moreover, a good intervention to improve C_r. Therefore, coaches should plan a strength training periodization that emphasizes on these 2 components. Athletes showing the initial highest C_r values will particularly benefit from explosive strength training. These positive adaptations can be expected after an 8-week intervention focusing on intensity rather than volume. For athletes with already low C_r, interventions should focus on increasing training volume and or intensity. As shown by the improvements in VJH_{peak} and in P_{peak}, explosive strength training will benefit to runners by increasing their general athletic performance.

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