Concurrent Training in Elite Male Runners: The Influence of Strength Versus Muscular Endurance Training on Performance Outcomes

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Abstract

Sedano, S, Marín, PJ, Cuadrado, G, and Redondo, JC. Concurrent training in elite male runners: The influence of strength versus muscular endurance training on performance outcomes. *J Strength Cond Res* 27(9): 2433–2443, 2013–Much recent attention has been given to the compatibility of combined aerobic and anaerobic training modalities. However, few of these studies have reported data related to well-trained runners, which is a potential limitation. Therefore, because of the limited evidence available for this population, the main aim was to determine which mode of concurrent strength-endurance training might be the most effective at improving running performance in highly trained runners. Eighteen well-trained male runners (age 23.7± 1.2 years) with a maximal oxygen consumption ($\dot{V}O_2max$) more than 65 $ml\cdot kg^{-1}\cdot min^{-1}$ were randomly assigned into 1 of the 3 groups: Endurance-only Group ($n = 6$), who continued their usual training, which included general strength training with Thera-band latex-free exercise bands and endurance training; Strength Group (SG; $n = 6$) who performed combined resistance and plyometric exercises and endurance training; Endurance-SG (ESG; $n = 6$) who performed endurance-strength training with loads of 40% and endurance training. The study comprised 12 weeks of training in which runners trained 8 times a week (6 endurance and 2 strength sessions) and 5 weeks of detraining. The subjects were tested on 3 different occasions (countermovement jump height, hopping test average height, 1 repetition maximum, running economy (RE), $\dot{V}O_2max$, maximal heart rate [HRmax], peak velocity (PV), rating of perceived exertion, and 3-km time trial were measured). Findings revealed significant time × group interaction effects for almost all tests ($p < 0.05$). We can conclude that concurrent training for both SG and ESG groups led to improved maximal strength, RE, and PV with no significant effects on the $\dot{V}O_2$ kinetics pattern. The SG group also seems to show improvements in 3-km time trial tests.

Key Words concurrent effect, muscle strength, interference, exercise, power

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Introduction

Distance running success is dependent on physiological attributes such as a high maximal oxygen uptake, especially in novice and young athletes (8,21). However, $\dot{V}O_2max$ is not a good predictor of distance running performance in elite athletes because neuromuscular and anaerobic characteristics might also be significant determinants of running performance (3,21,29,30). In highly trained athletes, variables such as peak treadmill running velocity during a maximal aerobic power test are better predictors of endurance performance because they are influenced not only by aerobic power but also by these neuromuscular and anaerobic characteristics (30). In fact, an improvement in race time would be the true indicator of improved performance (22); however, few studies include a time trial to assess improvements in this area (8,29,30). On the other hand, running economy (RE), which has been defined as oxygen uptake required at a given submaximal velocity (11), could also be considered as a determinant factor in running performance.

There are some neuromuscular characteristics associated with RE such as muscle force and stiffness, fiber-type distribution, elasticity, or neural input (14). These factors could also be improved by strength training (22,23,36), increasing the muscle work efficiency, and permitting aerobic activity at a lower oxygen consumption at submaximal intensities (11,27,29,36,37). Highly economic runners present lower energetic costs at submaximal speeds and, consequently, tend to run faster over a given distance or to run longer at a constant speed (14,19). Therefore, targeting RE provides a strong justification for the inclusion of strength training in distance runners' training program, as resistance training may improve mechanical efficiency, muscle coordination, and motor recruitment patterns and reduce relative intensity (18,20,22,23,28,29).

Many competitive endurance athletes perform concurrent strength and endurance training (concurrent training [CT]) to improve their specific endurance performance. However, combining strength and endurance training is difficult because of the conflicting demands of each type of activity (2,5,24,34,37). Moreover, many endurance runners refrain from CT to avoid gains in muscle mass (1), including either very little or no resistance training, and focusing on aerobic exercises. Nevertheless, it has been demonstrated that CT can elevate maximal muscle strength without muscle hypertrophy, which could also result in enhanced endurance performance in highly trained endurance athletes (1,14,17,25,29,32,34,36). However, few of these studies have reported data related to highly trained runners (14,25). Athletes participating in these studies could not be considered as absolute top-level endurance athletes because of their $\dot{V}O_2$max. Consequently, it might be difficult to transfer the results to elite athletes, where the trainability of $\dot{V}O_2$max is limited (22,23), and improvements in running performance could be related to neuromuscular characteristics and RE (22).

One unresolved question is the influence of different types of strength training on certain endurance related variables because the training-induced adaptations in the neuromuscular system differ according to the specific mode of exercise used for strength training (15). Some authors have reported improvements in endurance performance with explosive strength training (14,20,29), heavy resistance strength training (1,19,28,34), or circuit training (16). They have verified significant improvements in endurance performance after training; however, only 2 studies have been conducted to compare different strength training modes, when they are combined with endurance training (14,29), leading to opposite conclusions. On the other hand, detraining may be defined as the provisional or permanent reduction or withdrawal of a training stimulus, which may result in a decrease in athletic performance. The knowledge of the detraining phenomenon will provide coaches with useful information for developing exercise strategies. Whereas some studies show the effects of detraining adaptations after strength training or after endurance training in older adults (6,9) and in young men (26), no research has been conducted on this topic with regard to different CT modes in highly trained athletes.

Owing to the limited evidence available for highly trained runners, the main purpose of this study was to determine which mode of CT training might be the most effective at improving running performance and RE in highly trained runners. Moreover, another aim was to compare the influence of different CT modes on the detraining adaptations in these highly trained runners. The present study is consistent with the hypothesis that adding explosive and strength-endurance training to the usual endurance training of highly trained runners can improve running performance.

Methods

Experimental Approach to the Problem

Eighteen well-trained male runners (3,000–5,000 m) with a $\dot{V}O_2$max more than 65 $ml \cdot kg^{-1} \cdot min^{-1}$ and an average training history of at least 4 years participated in the study. They were randomized and divided into 3 groups according to their training programs: the Endurance-only Group (EG), who continued their usual training, which included general strength training and endurance training; the Strength Group (SG), and the Endurance-SG (ESG), who performed explosive or endurance-strength training, respectively, instead of general strength training. The independent variable was the treatment effect of 3 different 12-week concurrent training (CT) programs. The dependent variables were fat mass, countermovement jump (CMJ) height, hopping jump test average height, maximal strength (1 repetition maximum [1RM]), 3-km time trial, RE and peak velocity (PV), maximal heart rate, and maximal oxygen consumption in a treadmill running test. Each variable was measured on 3 occasions: 1 week before the start of the training program, after 12 weeks of training, and 5 weeks after the end of the program (detraining period). Two-way ANOVA with repeated measures and Bonferroni post hoc tests were conducted to assess the effects.

Subjects

Eighteen well-trained male runners (3,000–5,000 m) volunteered for the study. The study was approved by the Ethical Committee of the European University Miguel de Cervantes (Spain). Subjects were made fully notified and aware of the possible risks and signed an informed consent form before

Table 1. Characteristics and anthropometric data of the subjects (mean ± *SD*).

Group	Age (y)	Height (m)	Body mass (kg)	Body fat (%)
Endurance-only Group (n = 6)	23.50 ± 1.21	1.85 ± 0.05	69.50 ± 3.56	8.01 ± 2.26
Strength Group (n = 6)	24.10 ± 0.72	1.81 ± 0.02	68.50 ± 4.73	8.34 ± 2.35
Endurance-Strength Group (n = 6)	23.71 ± 1.81	1.79 ± 0.02	66.41 ± 5.38	9.15 ± 1.36

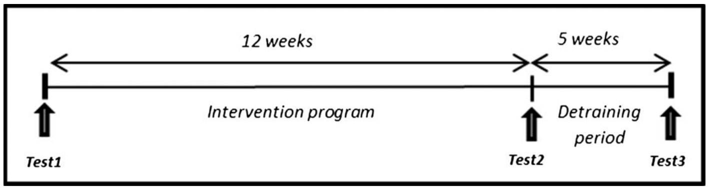

Figure 1. Testing schedule.

participation. The selection criterions were that the subjects were well-trained runners with a $\dot{V}O_2max$ higher than 65 $ml \cdot kg^{-1} \cdot min^{-1}$ and had an average training history of at least 4 years. All of them were competing at Spanish national level. Their subjects' characteristics and anthropometric data are shown in Table 1.

Procedures

The total duration of the study was 12 weeks, and it was completed during the specific phase of the periodization (January, February, and March), after 10 weeks of general training (October, November, and December), where runners practiced the same strength exercises that they would further perform during the intervention, to familiarize them. During the study, runners were not allowed to perform any other training that might influence the results, and they were previously informed about hydration, rest, and nutrition patterns. The subjects were tested on 3 different occasions with identical protocols as shown in the Figure 1.

Testing

The participants were familiarized with the testing procedures, having been tested regularly as part of their training program. All participants were required to attend 3 trial sessions. In the first, anthropometric profile and explosive and maximal strength were assessed. Two days later, in the second session, running tests at the treadmill were performed. Finally, in the third session, 48 hours apart, they carried out track running tests. Runners were instructed to refrain from intense exercise on the day preceding a test and to consume the same type of meal before testing. They were not allowed to consume products containing caffeine in the 4 hours immediately before a test. All the tests (except track running tests) were performed at the same time of the day in a climate-controlled (18–20° C) laboratory. All the measurements were highly reliable, with the intraclass correlation coefficient (ICC) ranging from 0.94 to 0.99 in anthropometric tests, from 0.92 to 0.94 in strength tests, from 0.96 to 0.97 in treadmill running tests, and from 0.95 to 0.97 in track running tests.

Anthropometric Data. Body mass and height were measured with a Holtain Stadiometer (British Indicators Ltd., Pembrokeshire, UK) (95–190 cm, accurate to 0.1 cm) and a SECA Tanita BC-418 MA electronic scale (Tanita Corporation of America, Inc., Arlington Heights, IL, USA) (0–150 kg, accurate to 0.1 kg). Body composition was assessed with the skinfold technique. The same ISAK level II anthropometrist obtained all anthropometric measurements in standardized order on the right side of the subject's body. Skinfold thickness was obtained with an AW610 Holtain (British Indicators Ltd., Pembrokeshire, UK) limiting caliper (0–48 mm, accurate to 0.2 mm). Six skinfolds were measured (triceps, subscapular, suprailial, abdomen, front thigh, and medial calf), and the subsequent fat mass percentage was calculated using the formula of Faulkner (10).

Explosive and Maximal Strength. Before the start of the strength tests, participants went through a standardized 20-minute warm-up. To assess explosive strength, runners performed 3 trials of countermovement jump on a jumping mat (SportJUMP 2 System; DSD, León, Spain), and the best result was used for the statistical analysis. The rest between

Table 2. Training schedule during the intervention for the 3 groups.

Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Interval training (Zone 3)	Strength training	Interval training (Zone 3)	Strength training	Cross-country or road running (0.5–1 h) (Zone 3)	Interval training (Zone 3) or Fartlek (0.5–1.5 h) (Zone 1 and 2)	Rest
	Cross-country or road running (0.5–1.5 h) (Zone 1)		Cross-country or road running (0.5–1.5 h) (Zone 1)			

trials was 60 seconds. After a 5-minute rest period, runners carried out a hopping test in which maximal vertical rebounds on both legs were executed from a standing position for 25 s. Subjects were instructed to rebound to the highest possible point with the smallest ground contact time and to keep hands on hips throughout the hops. Average height was recorded.

After a 10-minute rest period, a 1RM test, following the protocol established by the National Strength and Conditioning Association, was performed to measure the maximal strength. First, runners were instructed to warm up with a light resistance that easily allowed 5–10 repetitions. After a 1-minute rest period, we estimated a warm-up load that would allow them to complete 3–5 repetitions by adding 10–20%. After a 2-minute rest period, we estimated a near-maximum load that would allow for 2–3 repetitions by adding 10–20% again. Then, we introduced a 3-minute rest before consecutive load increases of 10–20% until the runner could complete only 1 repetition with a proper exercise technique. The 1RM test was calculated for the same exercises used in the training program in SG and ESG, which were always carried out in the same order: barbell squat (90 degrees), lying leg curl, seated calf raises, and leg extension. A 5-minute rest was taken between exercises.

Running Economy. Before the start of the RE test participants performed a 10-minute warm-up on the treadmill at 8 $km \cdot h^{-1}$. After that, RE was determined by means of a discontinuous protocol similar to that described by Cole et al. (8). Runners ran at 3 different speeds (12, 14, and 16 $km \cdot h^{-1}$) with a constant grade of 0% for 6 minutes. The average $\dot{V}O_2$ over the last minute at each of the running speeds was used as a measure of RE for a given speed, provided the difference between $\dot{V}O_2$ values was lower than 2.0 $ml \cdot kg^{-1} \cdot min^{-1}$. In instances where $\dot{V}O_2$ differences were greater than 2.0 $ml \cdot kg^{-1} \cdot min^{-1}$, $\dot{V}O_2$ measurements over the last 90 s were used. At the conclusion of each 6-minutes period, the treadmill speed was reduced to 4 $km \cdot h^{-1}$ for 2 minutes.

Treadmill Running Test. After a 30-minute rest period, $\dot{V}O_2$max, HRmax, PV, and rating of perceived exertion (RPE) were determined with an incremental test to exhaustion on a Technogym MD 500 treadmill (Technogym Wellness Company, Gambettola, Italy). First, they performed a 10-minute warm-up at 8 $km \cdot h^{-1}$. The test started at 12 $km \cdot h^{-1}$, and the initial velocity was progressively increased by 0.25 $km \cdot h^{-1}$ every 30 seconds until exhaustion, with a constant grade of 1%. Throughout the test, expired air was continuously sampled on a breath-by-breath basis with a SensorMedics 2900Z zirconium O_2 and infrared CO_2 analyzer (SensorMedics, Yorba Linda, CA, USA). The O_2 and CO_2 analyzers, interfaced to a personal computer, were calibrated before and were verified after each test. Heart rate was recorded at 5-second intervals by the S210 (Polar Electro, Kempele, Finland), and RPE was obtained with the 15-category Borg Rating of Perceived Exertion Scale. The maximal test was considered valid if it meet 2 of the following criteria: failure to continue the exercise stage despite strong verbal encouragement (volitional fatigue), a respiratory exchange ratio more than 1.15, and a heart rate within 10 beats of the age-predicted maximum, $207 - 0.7 \times$ age (12). The mean of the 5 highest $\dot{V}O_2$ values obtained during the test was defined as the $\dot{V}O_2$max, and PV was taken as the highest speed maintained for 30 seconds during the running. The second ventilatory threshold and its correspondent heart rate (HR_{VT}) were also assessed to establish the intensity of endurance training.

Table 3. Strength training details.*

Endurance-only group†	
Resistance exercise	Reps
Squat with band	25
Lying leg curl with band	25
Calf raises with band	25
Leg extension with band	25
Squat with band	25
Lying leg curl with band	25
Calf raises with band	25
Leg extension with band	25

Strength group	
Combined exercise	Sets/reps/load/reps/ rest between sets
Barbell squat + Vertical jumps over hurdles (40 cm)	3 sets (7 reps × 70% 1RM + 10 reps)/5 min
Lying leg curl + Horizontal jumps	3 sets (7 reps × 70% 1RM + 10 reps)/5 min
Seated calf raises + Vertical jumps over hurdles (40 cm)	3 sets (7 reps × 70% 1RM + 10 reps)/5 min
Leg extension + Horizontal jumps	3 sets (7 reps × 70% 1RM + 10 reps)/5 min

Endurance-Strength group	
Exercises	Sets/reps/load/rest between sets
Barbell squat	3 sets × 20 reps × 40% 1RM/ 60 s
Lying leg curl	3 sets × 20 reps × 40% 1RM/ 60 s
Seated calf raises	3 sets × 20 reps × 40% 1RM/ 60 s
Leg extension	3 sets × 20 reps × 40% 1RM/ 60 s

*1RM, 1 repetition maximum; Reps, repetitions.
†Circuit training. Rest between exercises 25 s/rest between sets 5 min.

Table 4. Descriptive data of explosive and maximal strength variables for the Endurance-only Group (EG; $n = 6$), the Strength Group (SG; $n = 6$), and the Endurance-SG Group (ESG; $n = 6$) on each test occasion (mean ± *SD*).*

Variable	Group	Time T1	Time T2	Time T3	Group *F* (*p*)	Time *F* (*p*)	Group × Time *F* (*p*)	T1-T2 *d*	T1-T3 *d*
CMJ (m)	EG	0.32 ± 0.02	0.33 ± 0.02	0.32 ± 0.03	34.265 (0.001)†	0.779 (0.477)	11.393 (0.001)†	0.05	−0.06
	SG	0.30 ± 0.03$_a$	0.33 ± 0.03$_b$	0.33 ± 0.03$_b$				0.80	0.74
	ESG	0.31 ± 0.04	0.31 ± 0.04	0.31 ± 0.04				0.14	0.18
Hopping test (m)	EG	0.26 ± 0.02	0.26 ± 0.03	0.26 ± 0.02	93.054 (0.001)†	0.603 (0.560)	8.527 (0.001)†	0.04	0.22
	SG	0.26 ± 0.02$_a$	0.27 ± 0.02$_b$	0.27 ± 0.02$_b$				0.87	0.60
	ESG	0.25 ± 0.04	0.26 ± 0.03	0.26 ± 0.04				0.33	0.25
1RM leg extension (kg)	EG	56.33 ± 4.80	58.83 ± 4.79	60.50 ± 4.80	295.579 (0.001)†	1.000 (0.391)	17.257 (0.001)†	0.52	0.86
	SG	52.16 ± 7.16$_a$	57.50 ± 6.89$_b$	58.66 ± 6.59$_b$				0.74	0.90
	ESG	54.66 ± 6.05$_a$	62.66 ± 5.78$_b$	65.50 ± 6.09$_c$				1.32	1.80
1RM seated calf raises (kg)	EG	115.00 ± 7.69	116.33 ± 8.21	116.50 ± 7.71	89.300 (0.001)†	1.003 (0.390)	8.341 (0.001)†	0.17	0.19
	SG	102.16 ± 10.10$_a$	120.00 ± 9.57$_b$	119.50 ± 10.48$_b$				1.76	1.71
	ESG	101.66 ± 6.85$_a$	123.83 ± 7.44$_b$	125.50 ± 7.17$_b$				3.23	3.48
1RM lying leg curl (kg)	EG	43.16 ± 3.06	44.00 ± 3.68	44.16 ± 3.76	154.993 (0.001)†	4.071 (0.039)†	15.852 (0.001)†	0.27	0.32
	SG	41.16 ± 3.76$_a$	46.33 ± 3.50$_b$	47.16 ± 3.54$_b$				1.37	1.60
	ESG	38.66 ± 2.33$_a$	47.66 ± 2.42$_b$	48.33 ± 2.42$_b$				3.86	4.15
1RM Barbell squat (kg)	EG	206.60 ± 17.66	210.55 ± 15.79	210.83 ± 14.48	159.762 (0.001)†	0.022 (0.978)	13.495 (0.001)†	0.22	0.24
	SG	202.51 ± 16.35$_a$	222.00 ± 17.05$_b$	219.24 ± 14.50$_b$				1.20	1.02
	ESG	194.83 ± 6.64$_a$	215.52 ± 7.55$_b$	214.35 ± 8.09$_b$				3.11	2.93

*T1, T2, and T3, 3 tests; *d*, effect size; CMJ, countermovement jump; 1RM, 1 repetition maximum.
†$p < 0.05$. Means in the same row for the same variable having the same subscript are not significantly different at $p < 0.05$.

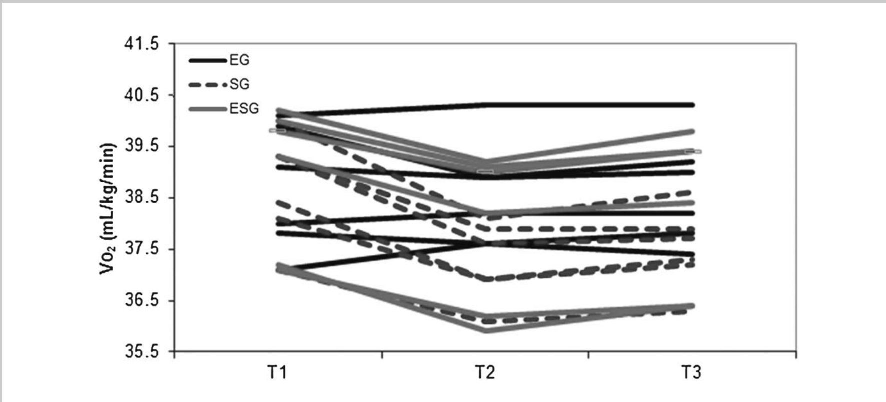

Figure 2. $\dot{V}O_2$ (milliliters per kilogram per minute) at 12 km·h^{-1} for Endurance-only Group (EG), Strength Group (SG), and Endurance Strength Group (ESG) in the 3 tests (T1, T2, and T3). Significant differences between T1 and T2 ($p = 0.008$, effect size [ES] = 0.90; $p = 0.001$, ES = 1.40) and T1 and T3 ($p = 0.001$, ES = 2.11; $p = 0.003$, ES = 1.87), both for SG and ESG.

Track Running Tests. After a 20-minute warm up, runners were randomly divided into 2 groups of 9 subjects to perform a 3-km time trial on a 400-m outdoor track. The split times were given to athletes during the 3 km (every 500 m). Total time employed was registered for each subject.

Training

During the intervention program, runners trained 8 times a week (6 endurance and 2 strength sessions). Endurance sessions were performed individually and strength sessions in groups of 6 athletes. They were always supervised by at least one experienced personal trainer with careful attention to proper exercise technique. Subjects recorded all training activities in a training log, which was reviewed and analyzed by an experienced researcher. During the study, players were not allowed to perform any other training that would impact the results. A more detailed description of the 12-week training program is presented in Table 2. After the intervention, all the groups continued with their usual strength training program which was similar to that used in the EG during the intervention.

Endurance Training. Endurance training consisted primarily of cross-country or road running for 0.5–1.5 hours, Fartlek for 0.5–1.5 hours, and interval training. During training, exercise heart rates were continuously monitored using heart rate monitors to divide the exercise into 3 HR zones using the HR_{VT} obtained in the maximal incremental test: (a) 75–85%, (b) 85–95%, and (c) 95–100% of the HR_{VT}. The total time spent on endurance training and the distribution of this training within the training zones were the same among groups.

Strength Training. In addition to the endurance training, runners performed a strength training program twice a week, which was different for each group. These training programs were focused on lower-limb muscles: quadriceps, hamstrings, and calf muscles. At the start of each strength training session, runners performed a 10-minute warm up at self-selected intensity on a treadmill followed by specific muscle stretching and a specific warm-up, with 1 set of 25 repetitions with very light loads for the lower body exercises. A percentage of each subject's 1RM for each exercise was used to determine the intensity each week. The intensity and number of repetitions performed for each exercise were changed progressively every 2 weeks and were adjusted for new 1RM measured at the midpoint (week 7) of training.

Endurance-only Group. During the intervention, this group performed general strength training as they usually carried out in this period of the season. This training included a circuit of 4 exercises focused on lower-limb muscles, where external resistance was provided by means of blue Thera-Band latex-free exercise bands (The Hygienic Corporation, Akron, OH, USA). Each circuit was repeated 3 times with 25 repetitions per exercise. Rest periods lasted 25 seconds between exercises and 5 minutes between series.

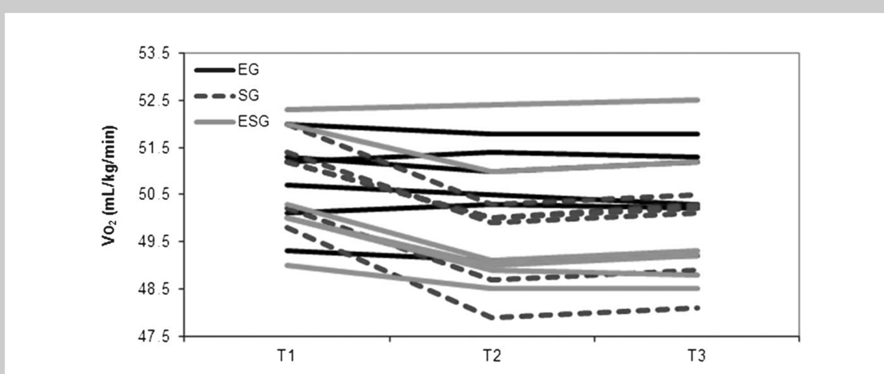

Figure 3. $\dot{V}O_2$ (milliliters per kilogram per minute) at 16 km·h^{-1} for Endurance-only Group, Strength Group (SG), and Endurance-SG in the 3 tests (T1, T2, and T3). Significant differences between T1 and T2 ($p = 0.015$, ES = 1.25) and T1 and T3 ($p = 0.020$, effect size = 1.20) for SG. EG, Endurance-only Group; ESG, Endurance-Strength Group.

TABLE 5. Descriptive data of peak velocity (PV), rating of perceived exertion (RPE), $\dot{V}O_2max$, HRmax, and $\dot{V}O_2$ 14 km·h^{-1} for the Endurance-only Group (EG; $n = 6$), the Strength Group (SG; $n = 6$), and the Endurance-SG (ESG; $n = 6$) on each test occasions (mean ± *SD*).*

Variable	Group	Time T1	Time T2	Time T3	Group F (p)	Time F (p)	Group × Time F (p)	T1-T2 d	T1-T3 d
PV (km•h^{-1})	EG	21.95 ± 1.21	22.12 ± 1.02	22.04 ± 1.08	87.533 (0.001)†	1.033 (0.380)	10.598 (0.001)†	0.14	0.07
	SG	20.91 ± 0.90_a	21.70 ± 0.78_b	21.87 ± 0.81_b				0.87	1.06
	ESG	21.45 ± 1.67_a	22.45 ± 1.69_b	22.66 ± 1.58_b				0.61	0.72
RPE	EG	17.25 ± 0.41	17.58 ± 0.49	17.16 ± 0.40	44.885 (0.001)†	0.600 (0.561)	8.995 (0.001)†	0.81	0.21
	SG	17.58 ± 0.49_a	16.66 ± 0.51_b	16.75 ± 0.61_b				1.87	1.69
	ESG	17.83 ± 0.51	16.91 ± 0.73	16.75 ± 0.75				1.80	2.11
$\dot{V}O_2max$ (ml•kg•min^{-1})	EG	68.80 ± 1.83	69.20 ± 2.05	69.11 ± 1.86	26.782 (0.001)†	1.030 (0.381)	2.948 (0.075)	0.21	0.17
	SG	68.83 ± 1.94	69.51 ± 1.98	69.48 ± 1.85				0.35	0.33
	ESG	70.73 ± 2.88	71.45 ± 1.76	71.73 ± 2.70				0.25	0.35
HRmax (b•min^{-1})	EG	201.16 ± 0.98	202.67 ± 1.36	201.71 ± 1.36	2.386 (0.128)	0.138 (0.872)	0.261 (0.901)	1.54	0.56
	SG	199.52 ± 1.51	200.01 ± 2.00	199.78 ± 1.52				0.32	0.17
	ESG	198.72 ± 2.07	199.33 ± 1.36	199.04 ± 1.67				0.29	0.15
$\dot{V}O_2$ 14 km•h^{-1} (ml•kg•min^{-1})	EG	46.95 ± 2.82	46.88 ± 2.14	47.05 ± 2.92	11.544 (0.001)†	17.706 (0.001)†	1.697 (0.217)	0.02	0.04
	SG	44.80 ± 1.11	42.48 ± 1.05	42.65 ± 0.97				2.09	1.93
	ESG	45.40 ± 1.09	44.30 ± 1.19	44.68 ± 1.01				1.01	0.66

**d*, Effect size.
†$p < 0.05$. Means in the same row for the same variable having the same subscript are not significantly different at $p < 0.05$.

Strength Group. Their training program included combined resistance and plyometric exercises. Sessions included barbell squat (range between 0 and 90 degrees of knee flexion), lying leg curl, seated calf raises, and leg extension performed with 3 sets of 7 repetitions with 70% of the maximal load. Each resistance exercise was combined with a plyometric exercise focused on lower limbs and performed on a hard synthetic surface. The rests between sets and between exercises lasted 5 minutes.

Endurance-Strength Group. Their training program included the same resistance exercises as SG, performed with 3 sets of 20 repetitions, with 40% of the maximal load. The rest period between series was of 60 seconds and between exercises was of 5 minutes.

On days when both strength and endurance training were scheduled, the runners were required to perform strength training in the first training session of the day and endurance training in the second session, at least 5 hours apart. A minimum of 24 hours separated each strength training session. Tables 2 and 3 show the general training regimen during the study and the strength training details, respectively.

Statistical Analyses

Normality of distribution was tested by means of the Kolmogorov-Smirnov test. Standard statistical methods were used for the calculation of the means and *SD*. One-way ANOVA was carried out to determine differences among the values at baseline of the 3 groups in all variables analyzed. Training-related effects were assessed using 2-way ANOVA with repeated measures (group × time). When a significant *F* value was achieved by means of Wilks's Lambda, Bonferroni post hoc procedures were performed to locate the pairwise differences. Bonferroni adjustment for multiple comparisons was applied. Magnitude of treatment effects within groups were estimated with Cohen's (7) effect size (ES). The within-group ES is defined as the difference between post test mean and pretest mean, divided by pretest *SD*. Rhea (31) classified ESs as "trivial" (<0.25), "small" (0.25–0.50), moderate (0.50–1.0), and "large" (>1.0). In addition, the reliability of measurements was calculated using ICC. The $p < 0.05$ criterion was used for establishing statistical significance.

Results

The Kolmogorov-Smirnov test suggested that all variables were distributed normally ($p > 0.05$). Results of comparative analysis (1-way ANOVA) among EG, SG, and ESG at baseline revealed that there were no statistically significant differences before the start of the training program.

Anthropometric Features

Results did not reveal interaction effects for body mass or body fat percentage.

Explosive and Maximal Strength

Results revealed significant time × group interaction effects both for explosive and maximal strength variables (Table 4). Bonferroni post hoc tests identified the differences between T1 and T2 ($p = 0.002$, $p = 0.001$) and between T1 and T3 ($p = 0.001$, $p = 0.007$), both for CMJ and hopping test in SG. On the other hand, Bonferroni post hoc tests found the differences between T1 and T2 ($p < 0.05$) and T1 and T3 ($p < 0.05$) in all the variables analyzed for both SG and ESG.

Treadmill Running Tests

In the RE test, results revealed significant time × group interaction effects for $\dot{V}O_2$ at 12 $km \cdot h^{-1}$ and $\dot{V}O_2$ at 16 $km \cdot h^{-1}$, but not for $\dot{V}O_2$ at 14 $km \cdot h^{-1}$. In $\dot{V}O_2$ at 12 $km \cdot h^{-1}$. Bonferroni post hoc tests identified the differences between T1 and T2 and between T1 and T3, both for SG and ESG (Figure 2). On the other hand, differences in $\dot{V}O_2$ at 16 $km \cdot h^{-1}$ appeared between T1 and T2 and T1 and T3, only in the SG group (Figure 3).

In the incremental test to exhaustion, results showed significant time × group interaction effects for both PV and RPE, but not for $\dot{V}O_2max$ or HRmax (Table 5). In RPE, differences were located between T1 and T2 ($p = 0.001$) and T1 and T3 ($p = 0.001$) in SG. In PV, differences were identified between T1 and T2 ($p = 0.001$, $p = 0.003$) and between T1 and T3 ($p = 0.001$, $p = 0.001$) for both SG and ESG.

Track Running Test

Results revealed significant time × group interaction effects in 3-km time trial. Differences were located between T1 and T2 and T1 and T3 for SG (Figure 4).

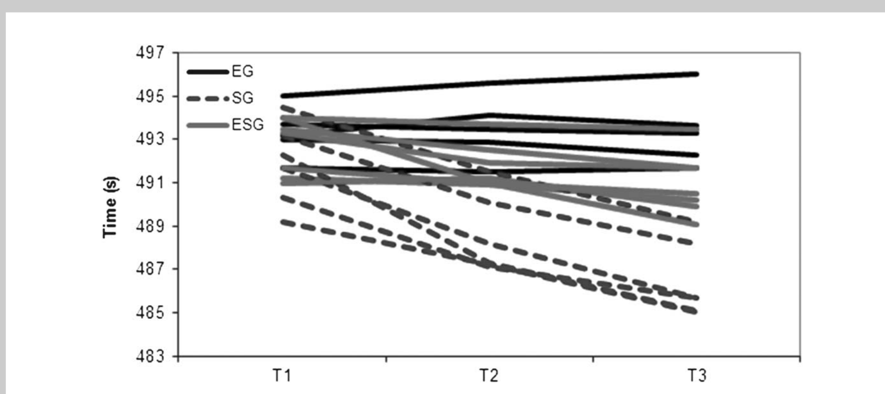

Figure 4. Track running test (3 km) results for Endurance-only Group, Strength Group (SG), and Endurance-SG in the 3 tests (T1, T2, and T3). Significant differences between T1 and T2 ($p = 0.002$, effect size [ES] = 0.69) and T1 and T3 ($p = 0.003$, ES = 0.99) for SG. EG, Endurance-only Group; ESG, Endurance-Strength Group.

Discussion

To our knowledge, this is the first study, which focuses on the comparison of the influence of different CT modes on running performance in highly trained runners and on the detraining adaptations of these CT modes. The rationale for this study was based on the hypothesis that endurance performance is influenced not only by central factors but also by peripheral factors relating to neuromuscular characteristics (3,21,29,30). The major finding of this study was that adding both explosive and strength-endurance training to the usual endurance training of highly trained runners resulted in increased running performance in terms of PV and RE without changes in variables such as $\dot{V}O_2$max or HRmax. Explosive strength training also resulted in improvements in time trial in a 3-km track running test, which can be considered as a true indicator of improved performance.

The present results revealed that there was a gain in maximal strength (i.e., 1RM) both in SG and in ESG, whereas there were no changes during the intervention in EG. Those improvements were maintained during the detraining period. Studies developed in untrained middle-aged men (15) and in well-trained triathletes (17) also found gains in maximal strength with CT. These improvements can be achieved with no increase in body weight (1,19,27), which seems to be a concern among runners.

Balabinis et al. (2) stated that vertical jump performance could be improved without any specific jump training because of exercises such as squat. However in the present study, only the group that included plyometric training improved explosive strength in terms of jumping ability. Another study, which did not include plyometric exercises, did not report significant improvements in vertical jump with CT (13). The divergent findings concerning vertical jump can, however, be attributed to varying methodologies among study training protocols.

Research in the literature focused predominantly on the impact of endurance training on strength performance and not on the effects of resistance training on endurance performance. Moreover, the scientific literature is equivocal concerning the impact of resistance training on endurance performance. Over the past decades, one of the most popular beliefs in exercise physiology has been that endurance performance is limited by central factors such as $\dot{V}O_2$max or HRmax. However, it has been observed that some endurance athletes are unable to perform well in a given sport event, although their oxygen transport and utilization capacity are high. Furthermore, results obtained in the present study revealed that both SG and ESG improved $\dot{V}O_2$ at 12 $km \cdot h^{-1}$ and PV without significant changes in $\dot{V}O_2$max or HRmax. Strength Group also improved RE at 16 $km \cdot h^{-1}$ and RPE ratings. All those changes were maintained during the detraining period.

In line with the present study, studies of endurance athletes have shown that replacing some aerobic training with strength training improves aerobic performance without producing changes in variables such as $\dot{V}O_2$max or HRmax (17,18,27,29,37), especially when trained subjects are involved. Conversely, some authors reported significant improvements in $\dot{V}O_2$max with resistance training (2,15). However, these could also be related with the low initial level of aerobic capacity in the samples used. The principle of training specificity predicts that endurance training alone should produce a greater increase in $\dot{V}O_2$max than CT. Our data did not support this principle, however, probably owing to the initial high level of the aerobic capacity of the subjects, with limited trainability. The addition of strength training did not negatively affect the development of $\dot{V}O_2$max, which is in line with other studies (2,4,18,27,32). This indicates that neuromuscular and anaerobic characteristics of muscles contribute to running performance and that the central factors are not the only determinants of performance (27,30), especially when variables such as $\dot{V}O_2$max are held constant, which is the case in well-trained athletes (22). These results collectively demonstrate compatibility rather than interference between strength and endurance training in athletes, supporting the concept of an "additive effect" (27).

Results related to RE are in line with those of Paavolainen et al. (29) in trained male distance runners, Jonhston et al. (19) in female distance runners, Millet et al. (27) in triathletes, and Hoff et al. (18) in cross-country skiers who indicated that athletes who all performed combined strength and endurance training had a superior movement economy that the athletes who merely continued their regular endurance training lacked. Conversely, Millet et al. (27) in well-trained triathletes and Levin et al. (25) in well-trained cyclists did not find improvements in RE, relating this lack of improvements to the fact that they were highly trained athletes, who have a narrow margin of improvement. However, our results revealed improvements in RE in highly trained athletes, which is in line with other findings in well-trained cyclists (36).

The improvements in RE could be partially related to the improvements in maximal strength, as muscle fiber tension developed in each running movement would decrease to a lower percentage of the maximal values (1,5,18,33). This might also contribute to a reduced degree of muscle fiber exhaustion. According to the size principle of muscle fiber type recruitment, this would allow reduced reliance on type II muscle fibers for the same submaximal load, improving economy and reducing overall muscle fatigue (4,27). On the other hand, strength training programs might result in better muscular coordination and therefore better mechanical efficiency of running style, which reduces oxygen consumption for the same submaximal intensity (18,19,29,39). This is particularly the case with the group that performed explosive training, as they improved economy even in higher velocities of running. Moreover, Cadore et al. (4) pointed out that in most studies in which strength training improves economy, the type of training carried out includes explosive strength training.

Contrary to the results obtained in the present study, some authors have pointed out that RE could be improved using heavy weight strength training but not with explosive strength training (1,14). However, the samples used by these authors did not present previous experience with a resistive training protocol, and this could have contributed to their improvement levels. Jonhston et al. (19) and Ronnestad et al. (32) also found that traditional resistance training improves endurance performance in both trained and untrained individuals. Conversely, Spurrs et al. (35) and Turner et al. (38) have shown that 6-week plyometric training led to improvements in RE, as this type of training has the potential to increase activation of the motor units and to increase the stiffness of the muscle-tendon system, which allow the body to store and use elastic energy more effectively. Our results confirm those results since demonstrated that not only an explosive but also a low-resistance training program are effective to improve endurance performance. Balabinis et al. (2) reported that a low-resistance training program combined with plyometrics was not effective in improving aerobic capacity in basketball players. The concept of movement specificity suggests that the type of resistance training used should closely model the movement that will be performed in competition (22). Consequently, Paavolainen et al. (29) and Jones and Bampouras (20) stated that explosive training, mimicking the eccentric phase of running, is most likely to improve the use of stored elastic energy and motor unit synchronization, which increases the ability of the lower-limb joints to act stiffer on ground contact. Moreover, Millet et al. (27) stated that explosive-strength training leads to different muscular adaptations than does typical heavy weight training; e.g., a greater increase in the rate of activation of the motor units. Yamamoto et al. (39) also stated that explosive training benefits the performance of trained cyclists.

On the other hand, peak treadmill running performance is a good predictor of track running performance (29). The increased time to exhaustion in SG and ESG might be a result of the superior improvement in RE, as it could lead to a reduction in $\dot{V}O_2$, depletion of energy stores, delayed accumulation of metabolites, and an attenuated increase in core body temperature (32). Rating of perceived exertion is a subjective indirect measure of performance, and it can be used as a sensitive predictor of time to exhaustion during exercise. Interestingly, at the postintervention test, athletes in SG reported significant lower RPE rates during the treadmill running test, whereas there was no change in ESG or EG. These results are comparable with those registered in cyclists (33). In contrast, Hausswirth et al. (17) did not find variations in perceived exertion after 5 weeks of CT in well-trained triathletes.

Track Running Tests

Our results revealed that there was a significant gain in 3-km time trial with explosive strength training, which might be a true indicator of improved performance (22,40). This improvement was also maintained during the detraining period, although Cole et al. (8) stated that muscle strength and power were not significantly related to 5-km race time in adolescent male cross-country runners. Paavolainen et al. (29) also showed improvements in 5-km running performance of well-trained male endurance athletes with CT that included explosive strength training. They related these improvements to neuromuscular characteristics and to improvements in RE.

Practical Applications

Although, well-trained runners still refrain from strength training for fear that it will increase their muscle mass and consequently decrease their performance capacity, this article contains information about the beneficial effects of CT in runners performance. Based on the results, we can conclude that CT, including both explosive and endurance-strength training, led to improved maximal strength, RE, and PV with no significant effects on the $\dot{V}O_2$ kinetics pattern. Therefore, its inclusion in the training program of well-trained endurance athletes is recommended for coaches. Moreover, explosive strength training also led to improvements in time trial, which is especially significant for a distance runner, as it could be considered as a true indicator of running performance. On the other hand, the fact that achievements can subsequently be maintained with normal endurance training is also important for practitioners. Moreover, coaches must take into account that regular endurance training can maintain the gains for several weeks after the 12-week program.

Finally, it may be concluded that CT should be an integral component of well-trained athletes' practice regimen because of its potential to improve the performance. However, it must be taken into consideration that our sample is not as wide as to claim that results previously mentioned could easily be extrapolated. Therefore, further studies with a greater sample must be developed.

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