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Effects of 20 Weeks of Endurance and Strength Training on Running Economy, Maximal Aerobic Speed, and Gait Kinematics in Trained Runners

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Abstract: Objective: This study aims to evaluate the effects of a 20-week endurance and strength training program on running economy and physiological, spatiotemporal, and neuromuscular variables in trained runners. Methods: A total of 18 runners (13 males and 5 females) completed a running economy test (2 bouts of 5 min at 3.06 m·s^{-1} for females and at 3.61 m·s^{-1} for males) and a graded exercise test (5 min at 2.78 m·s^{-1}, with speed increasing by 0.28 m·s−1 every 1 min until volitional exhaustion). During the training program, the participants completed different low-intensity continuous running sessions, high-intensity interval running sessions, and auxiliary strength training sessions. Results: Running economy, measured as oxygen cost and energy cost, increased by 4% (p = 0.011) and 3.4% (p = 0.011), respectively. Relative maximal oxygen uptake (VO_{2max}) increased by 4.6%. There was an improvement in the speed associated with the first (VT_1) and the second ventilatory threshold and with the maximal aerobic speed by 9.4, 3.7, and 2.8% (p = 0.000, p = 0.004, and p = 0.004, respectively). The %VO_{2max} value of VT_1 increased by 4.8% (p = 0.014). Conclusions: These findings suggest that a 20-week endurance and strength training program significantly improves performance and physiological factors without changing the runner's biomechanics.

Keywords: performance; physiology; biomechanics; training; strength

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1. Introduction

Endurance running performance is influenced by a complex interaction of factors, such as (1) maximal oxygen uptake (VO_{2max}) [1,2], (2) lactate threshold [3,4], (3) second ventilatory threshold [5], and (4) running economy (RE) [6]. Traditionally, VO_{2max} is considered the best laboratory measure to understand endurance running performance [1]. However, it has been demonstrated that once a minimum VO_{2max} level has been achieved (~70 mL·kg^{-1}·min^{-1}), running performance is mainly determined by RE [7]. RE is the steady-state oxygen uptake (VO_2) required at a given submaximal running intensity and is typically expressed as oxygen or energy cost per distance [8]. An incremental running testing performed until the point of exhaustion also allows for the definition of the different training zones (e.g., intensities lower than the velocity of the aerobic threshold, intensities between the velocity of the aerobic and anaerobic threshold, intensities between the velocity of the anaerobic threshold, and the velocity of VO_{2max} and intensities higher than the velocity of VO_{2max}) [9]. The ventilatory anaerobic threshold is defined as the exercise intensity above which there is a disproportionate increase in ventilation relative to oxygen consumption [5].

Factors such as training, environment, physiology, biomechanics, and anthropometry influence RE [6]. RE can be altered acutely with footwear modifications [10,11] or chronically through training adaptations (physiological and biomechanical factors) [7,12]. Kinematics [13] and kinetics parameters [7] can also impact RE. Thus, more efficient mechanics lead to less energy wastage [14] by using the muscles' ability to store and release elastic energy. In this way, a lower vertical displacement and higher vertical and leg stiffness (K_{leg}) have shown significant associations with better RE [15].

Previous research has suggested that different training strategies may influence RE and running performance [16] due to improved muscle work and optimization of running gait [17]. Similarly, strength training has shown performance improvements related to a better RE [18]. This is due to enhanced intramuscular coordination of the lower limbs and an increase in muscle coactivation and K_{leg} [19]. Medium-load (60–85% 1RM) and high-load (>85% 1RM) strength exercises and plyometric exercises carried out 2–3 times per week appear to be efficient in enhancing RE [18]. Similarly, endurance training improves the functionality of skeletal muscle mitochondria and hematological changes [6] with mainly two endurance training strategies, interval and continuous training methods [20]. The influence of these two endurance training methods has usually been studied in isolation in the literature [20].

However, few studies have analyzed the changes in RE following a combined strength and endurance training program. Rodriguez-Barbero et al. [21] showed an improvement of around 5% in RE in recreational and well-trained runners after 8 weeks of a regular endurance training program without changes in spatiotemporal parameters and K_{leg}. However, to our knowledge, no studies have analyzed changes in running performance after long-term training. Therefore, this study aimed to evaluate the effects of a 20-week endurance and strength training program on RE and physiological, spatiotemporal, and neuromuscular variables in nationally trained long-distance runners. We hypothesized that runners would improve their RE although without significantly modifying their biomechanics.

2. Materials and Methods

2.1. Participants

A total of 18 nationally trained runners, 13 males and 5 females (age: 25.56 ± 5.20 years; body mass: 58.70 ± 5.45 kg; height: 170.24 ± 7.93 cm; years of experience in national events: 5.71 ± 1.82; performance: 33:41 ± 04:21 min:ss in 10 km; World Athletics score: 831.89 ± 149.26 points) were recruited for this study. Participants met the following inclusion criteria: running at least three days per week without injuries during the previous three months before the study, and faster times <35 and 40 min in 10 km for males and females, respectively. Following the guidelines of McKay et al. [22] the participants were classified as *nationally trained* runners.

Before the study, all participants were informed about the testing protocols and the possible risks involved. They provided written informed consent. The study was performed according to the principles of the Declaration of Helsinki (December 2013, Brazil) and the experimental protocols were approved by the ethics committee of the local university (CEIC926).

2.2. Experimental Design

A pre-test–post-test design was used to assess the effects of a 20-week endurance and strength training program. Participants were instructed to avoid strenuous exercise (no intense exercise in the previous 48 h) and caffeine and alcohol intake 24 h before each visit. Participants were tested at the same time and asked to replicate their nutrition, sleep, and training patterns before each session. All data collection was performed at the same time of day and under similar environmental conditions (529 m altitude, 20–25 °C, and 35–40% relative humidity). Furthermore, each participant used the same footwear model in the two visits to control the effect of shoe mass and footwear properties.

2.3. Procedure

First, height was measured to the nearest 0.1 cm, and body mass was assessed to the nearest 0.1 kg with a portable stadiometer and caliber (Seca, Bonn, Germany). Then, all participants completed a warm-up that consisted of a 10 min run at a self-selected pace on a treadmill (HP Cosmos Pulsar, H/P/Cosmos Sports & Medical GMBH, Nussdorf-Traunstein, Germany) without stretching or mobility exercises.

Subsequently, all participants completed the RE test consisting of 2 bouts of 5 min running at 3.06 $m \cdot s^{-1}$ for females and 3.61 $m \cdot s^{-1}$ for males, separated by 2 min of passive recovery (standing quietly on the treadmill) [7]. To obtain further confirmations about VO_2 values at steady-state, respiratory exchange ratio (RER) values were measured, which were below 1.0 for all participants (0.85 ± 0.04). The treadmill slope was kept at 1% to most accurately reflect the energetic cost of outdoor running [23]. Then, all participants completed the grade exercise test. The test started at 2.78 $m \cdot s^{-1}$ for 5 min, and the speed increased by 0.28 $m \cdot s^{-1}$ every 1 min until volitional exhaustion.

2.4. Measurements

During the test, respiratory variables were measured using a gas analyzer (CPX Ultima Series MedGraphics, St. Paul, MN, USA) calibrated before each session (CO_2 4.10%; O_2 15.92%), with an intra-session variability lower than 0.5%.

RE was measured as the energy cost of running ($kJ \cdot kg^{-1} \cdot km^{-1}$), with the average respiratory exchange ratio (RER) during the same period and VO_2 caloric equivalent (kcal/L $O_2{}^{-1}$) used in previous research [8]. The equation used was the following Lusk [24]:

$$VO_2 \cdot \text{caloric equivalent} \cdot s^{-1} \cdot \text{body mass}^{-1} \cdot K$$

where VO_2 is measured in liters per minute, caloric equivalent is measured in kilojoules per liter, speed (s) is measured in meters per minute, body mass is measured in kilograms, and distance (K) is 1000 meters. Also, RE was expressed in terms of oxygen cost required at a given submaximal running intensity ($mL \cdot kg^{-1} \cdot min^{-1}$).

In the grade exercise test (GXT), the average VO_2 value obtained during the last 30 s of the final running stage was considered as VO_{2max} when at least two of the following criteria were fulfilled [25]: (1) a plateau in VO_2 (an increase of less than 1.5 $mL \cdot kg^{-1} \cdot min^{-1}$ in two consecutive intensities); (2) RER > 1.10; (3) maximal heart rate values above 90% of the age-predicted maximum (220-age); and (4) indication of maximal exhaustion by the athlete. The speed of the final running stage where VO_{2max} occurred was the considered maximal aerobic speed (MAS). The first ventilatory threshold (VT_1) was identified by an increase in VE/VO_2 with no concurrent increase in VE/VCO_2 and a departure from the linearity of ventilation. The second ventilatory threshold (VT_2) was identified by a non-linear increase in the VE/VCO_2 curve concomitant to a second strong increase in VE/VO_2, with a further increase in exercise intensity [26].

The spatiotemporal parameters of the gait cycle [contact time (CT), step frequency (SF), step length (SL), flight time (FT), K_{leg}, and vertical oscillation] were measured for each step during both tests using an inertial measurement unit (Stryd Power Meter, Stryd Inc., Boulder, CO, USA) with a sampling frequency of 1000 Hz. The Stryd Power Meter device has shown adequate validity and reliability compared to optical measurement devices and slow-motion recording to measure spatiotemporal parameters [27] and K_{leg} [28]. For the data analysis, spatiotemporal data were taken from the RE tests, and the velocity of VO_{2max} of the pre-test and the same velocity of the post-test.

2.5. Training Characteristics

Twenty weeks (October 2023 to March 2024) of regular endurance running training combined with strength training were retrospectively analyzed for all participants (Figure 1). The participants were part of a local running club and shared the same coach. Training sessions lasted between 60 and 90 min. They included continuous running at moderate-intensity sessions (zone 1, around 60% of MAS), high-intensity interval sessions (zones 2 and 3, between 80–110% of the maximum aerobic speed [MAS]), and isolated strength training sessions with medium loads (50–70% of one repetition maximum [1RM]), in combination with core exercises, plyometrics, and 50–100 m sprint repetitions. Strength training was aimed at improving trunk strength-endurance capacity with low-intensity, high-volume exercises, along with the development of abilities related to the stretch-shortening cycle with plyometric exercises and leg muscle hypertrophy and strength with isolated strength exercises. Participants followed a pyramidal training intensity distribution characterized by a decreasing training volume from z1 to z2 and z3, respectively. Approximately 80% of the volume was conducted in z1, with the remaining 20% in z2 and z3 [29]. Two training microcycles and a strength session are shown in Table 1 as an example. Throughout the program, participants tracked a significant portion of the training sessions using platforms such as Garmin and/or Strava to monitor the training load accurately. No athlete had to withdraw from the study due to injury.

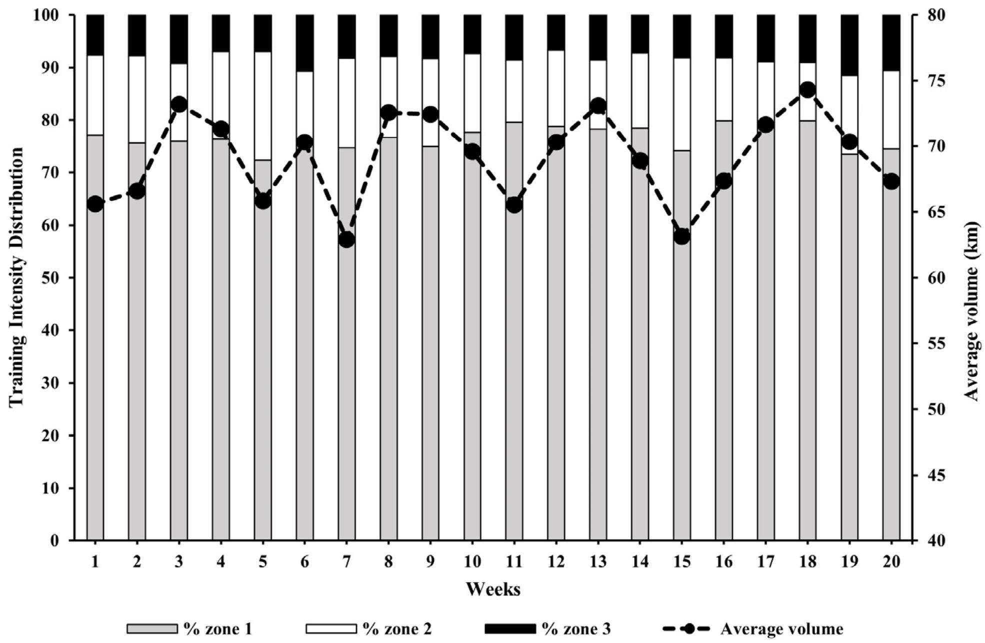

Figure 1. Endurance training intensity distribution for the 20 weeks of training.

Table 1. Example of two types microcycles and a strength session of the participants.

		Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
Week **3**	Type of session	Continuous running	High-intensity interval	Continuous running	Strength	High-intensity interval	Continuous running	Continuous running
	Volume	60 min 12–14 km	55 min 10–12 km	70 min 14–16 km	50 min	70 min 12–14 km	80 min 15–17 km	80 min 15–17 km
	Intensity	60% MAS	105% MAS	65% MAS	55% RM	90% MAS	60% MAS	65% MAS
	Examples of high-intensity interval sessions	3 × (6 × 400 m + 1000 m) with 1 and 2 min of passive recovery 2 × 16 min threshold training with 2 min of passive recovery 15 × 400 m with 75 s of passive recovery						
Week 18	Type of session	Continuous running	High-intensity interval	Continuous running + technique	High-intensity interval	Strength	Continuous running	
	Volume	60 min 10–12 km	70 min 12–15 km	50 min 8–10 km	80 min 14–16 km	50 min	90 min 18–20 km	
	Intensity	60% MAS	105% MAS	60% MAS	90% MAS	65% RM	65% MAS	
	Examples of high-intensity interval sessions	12 × 500 m with 2 min of passive recovery 8 × 5 min threshold training with 2 min of passive recovery 16 min threshold training + 8 × 400 m with 2 and 1 min and 30 s of passive recovery						
Strength session	Strength exercises	4 bouts of 6 repetitions at 60% of 1RM with 1 min recovery		Unipodal dead weight Hip thrust		Bulgarian squat Squat		Charged Gluteal bridge
	Core exercises	4 bouts of 12 repetitions		Dead bug Crunches	Mountain climbers Plank	Leg raises		
	Plyometrics exercises	4 bouts of 5 repetitions		Box jumps	Drop jumps	Vertical jumps	Strides	
	Sprint	8 repetitions of 100 m at maximum speed with 1 min recovery						

2.6. Statistical Analysis

Data were represented as mean ± SD. Data were screened for normality using a Shapiro–Wilk test. Paired t-tests were used to analyze the pre–post differences produced in the physiological and spatiotemporal variables before and after the 20 weeks. Effect sizes (ESs) were measured using Cohen's d, and values of 0.2, 0.5, and above 0.8 were considered small, medium, and large, respectively [30]. The level of significance used was $p < 0.05$. SPSS 29.0 (SPSS Inc., Chicago, IL, USA) was used for the data analysis.

3. Results

The results from the physiological, spatiotemporal, and neuromuscular variables of the RE tests are presented in Table 2. There were significant differences ($p < 0.05$) between time points (pre–post) in RE (expressed as oxygen cost [OC] and energy cost [EC]). However, there were no significant differences in spatiotemporal and neuromuscular variables during the RE test. OC and EC were significantly higher in the post-test (43.55 ± 3.23 vs. 45.36 ± 3.18 mL·kg^{-1}·min^{-1} and 4.28 ± 0.25 vs. 4.43 ± 0.21 kJ·kg^{-1}·km^{-1}, respectively).

Table 2. Results of physiological, spatiotemporal, and neuromuscular variables of the RE test.

Variables	Time Points		Paired *t*-Test	
	Pre	Post	ES	*p*
OC ($mL \cdot kg^{-1} \cdot min^{-1}$)	43.55 ± 3.23	45.36 ± 3.18	0.677	0.011
EC (kJ/kg/km)	4.28 ± 0.25	4.43 ± 0.21	0.672	0.011
CT (s)	0.229 ± 0.015	0.229 ± 0.016	0.051	0.830
FT (s)	0.136 ± 0.019	0.135 ± 0.017	0.078	0.746
SF (step/min)	164.64 ± 5.90	165.22 ± 5.45	0.144	0.549
SL (m)	1.27 ± 0.11	1.26 ± 0.10	0.156	0.517
K_{leg} ($kN \cdot m^{-1}$)	8.99 ± 1.38	9.01 ± 1.30	0.020	0.934
Vertical oscillation (cm)	8.62 ± 0.97	8.81 ± 0.81	0.332	0.177

Data are presented as mean ± standard deviation. OC, oxygen cost; EC, energy cost; CT, contact time; FT, flight time; SF, step frequency; SL, step length; K_{leg}, leg stiffness.

The results from the physiological, spatiotemporal, and neuromuscular variables during the GXT are shown in Table 3. There were significant differences ($p < 0.05$) between time points (pre–post) in the speed of VT_1, VT_2, and MAS, in the oxygen cost of VT_1 and VT_2, in the relative VO_{2max}, and in the percentage of VT_1. There was a significantly higher speed of VT_1 (13.44 ± 1.65 vs. 14.67 ± 1.61 $km \cdot h^{-1}$), VT_2 (17.94 ± 1.86 vs. 18.61 ± 1.72 $km \cdot h^{-1}$), and MAS (19.44 ± 2.09 vs. 20.00 ± 2.03 $km \cdot h^{-1}$) in the post-test compared to the pre-test. The oxygen cost of VT_1 (46.69 ± 6.29 vs. 51.38 ± 4.83 $mL \cdot kg^{-1} \cdot min^{-1}$) and VT_2 (58.83 ± 8.13 vs. 62.53 ± 6.61 $mL \cdot kg^{-1} \cdot min^{-1}$) significantly increased in the post-test. The relative VO_{2max} was significantly higher (61.55 ± 8.77 vs. 64.53 ± 7.00 $mL \cdot kg^{-1} \cdot min^{-1}$) in the post-test. The percentage of VT_1 significantly increased (76.06 ± 3.95 vs. 79.90 ± 5.28%) in the post-test (Figure 2). However, there were no significant differences in the spatiotemporal and neuromuscular variables during the GXT.

Table 3. Results of physiological, spatiotemporal, and neuromuscular variables of the GXT test.

Variables	Time Points		Paired *t*-Test	
	Pre	Post	ES	*p*
VT_1 speed ($km \cdot h^{-1}$)	13.44 ± 1.65	14.67 ± 1.61	1.296	<0.001
VT_2 speed ($km \cdot h^{-1}$)	17.94 ± 1.86	18.61 ± 1.72	0.778	0.004
Maximal aerobic speed ($km \cdot h^{-1}$)	19.44 ± 2.09	20.00 ± 2.03	0.788	0.004
Oxygen cost of VT_1 ($mL \cdot kg^{-1} \cdot min^{-1}$)	46.69 ± 6.29	51.38 ± 4.83	1.089	<0.001
Oxygen cost of VT_2 ($mL \cdot kg^{-1} \cdot min^{-1}$)	58.83 ± 8.13	62.53 ± 6.61	0.793	0.004
Relative VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$)	61.55 ± 8.77	64.53 ± 7.00	0.673	0.011
Absolute VO_{2max} ($L \cdot min^{-1}$)	3.63 ± 0.71	3.96 ± 0.96	0.397	0.110
% of VT_1	76.06 ± 3.95	79.90 ± 5.28	0.643	0.014
% of VT_2	95.72 ± 3.23	96.95 ± 1.96	0.367	0.138
CT at VO_{2max} speed (s)	0.176 ± 0.014	0.173 ± 0.015	0.256	0.293
FT at VO_{2max} speed (s)	0.140 ± 0.013	0.145 ± 0.015	0.480	0.058
SF at VO_{2max} speed (step/min)	190.89 ± 8.32	190.56 ± 7.81	0.115	0.633
SL at VO_{2max} speed (m)	1.70 ± 0.173	1.73 ± 0.17	0.399	0.109
K_{leg} at VO_{2max} speed ($kN \cdot m^{-1}$)	8.59 ± 1.21	8.90 ± 1.29	0.213	0.379
Vertical oscillation at VO_{2max} speed (cm)	7.25 ± 0.69	7.35 ± 0.66	0.413	0.098

Data are presented as mean ± standard deviation. VT_1, first ventilatory threshold; VT_2, second ventilatory threshold; VO_{2max}, maximal oxygen uptake; CT, contact time; FT, flight time; SF, step frequency; SL, step length; K_{leg}, leg stiffness.

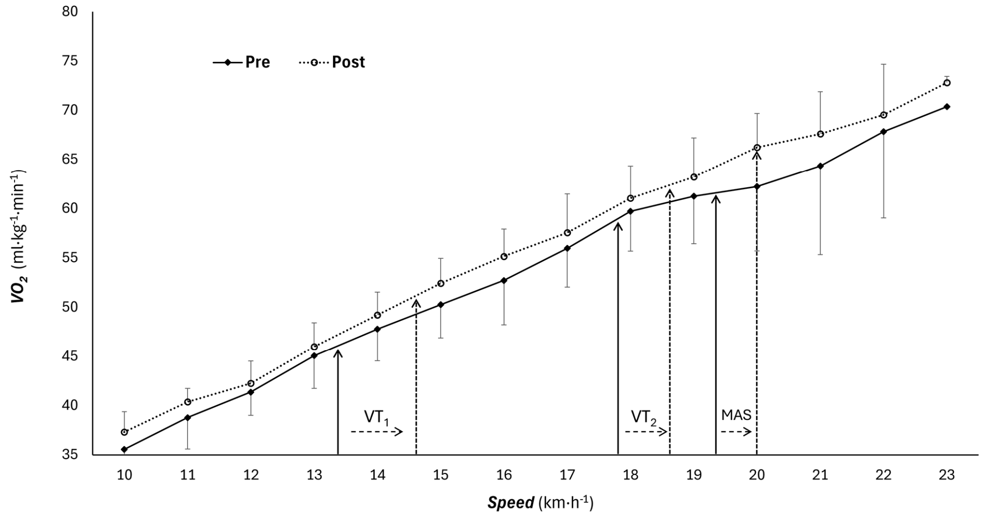

Figure 2. Changes in VO_2 during the GXT after the training program.

4. Discussion

This study aimed to analyze the effects of 20 weeks of regular endurance and strength training on RE and physiological, spatiotemporal, and neuromuscular variables in national long-distance runners. The main findings of our study were as follows: (1) a 3.5% deterioration in RE; (2) a 5% improvement in VO_{2max} relative to body mass; (3) an improvement in MAS, VT_1, and VT_2 speeds; and (4) an increase in $\%VO_{2max}$ of VT_1 but not of VT_2. In addition, to assess biomechanical variables, we used fixed speeds during the RE test and the MAS during the pre-test. However, there were no associated biomechanical changes at these speeds.

Our results indicate an improvement in $VO_{2max,}$ and MAS that occurred simultaneously with a decrease in RE. In that sense, previous studies have found that VO_{2max} and exercise economy are inversely related [31,32]. For this reason, the increase in speed of VT_1 (9.4%), VT_2 (3.7%), and MAS (2.8%) after the training program in our study was accompanied by a higher oxygen cost/energy cost (worse RE) during GXT (9.1, 5.9, and 4.6% for VT_1, VT_2, and MAS, respectively) and the fixed speed in the RE test (4.1 and 3.5% for oxygen and energy cost, respectively). In our study, the improvement in VO_{2max} was ~5%. However, well-trained runners improved their running performance (800 m and 2 miles) during 8 weeks of regular training without changes in VO_{2max} or RE [33]. In a longitudinal study with female and male elite middle-distance and distance runners [34], VO_{2max} remained unchanged after one, two, and three years of training, while running performance improved significantly in the male runners. A possible explanation for this phenomenon could be that highly trained/elite runners could have reached a biological limit in VO_{2max} after several years of consistent training [34], while in our study, the participants (well-trained but not elite runners) could have not reached that biological limit, and only 20 weeks of training were sufficient to find some changes in that parameter. Due to the linear relationship between oxygen uptake and intensity during a GXT [35], it is expected that the increase in VO_{2max} will be accompanied by a loss of efficiency (higher oxygen/energy cost), as we found in our study (Figure 2). In addition, it is possible that in the last weeks of training during our study, the training capacity that was more developed was aerobic power due to the proximity to some cross-country competitions. Therefore, it appears that physiological adaptations after a period of regular endurance and strength training are dependent on the most developed capacities at the times closest to the laboratory evaluations performed.

This physiological adaptation mentioned above could be explained by the training stimulus applied during the training period. The participants displayed a pyramidal TID during the 20 weeks of training, with 6–8% of training in z3 close to and higher than the intensity of VO_{2max}/MAS. These improvements could have been induced by increased time at high VO_{2max} and distance completed at higher speeds [36,37]. A high fraction (%) of VO_{2max} during high-intensity sessions plays a decisive role in the improvements of parameters such as VO_{2max}, so the inclusion of interval training sessions close to 90% and above 105% of MAS could have resulted in the high %VO_{2max} during these sessions. Previous studies have shown that continuous and interval training promotes significant improvements in VO_{2max} [38–40]. Gonzalez-Mohino et al. [41] found that a 6-week high-intensity interval training program increases MAS by 7.9% in recreational runners, and Denadai et al. [42] claim that 4 weeks of high-intensity interval training increases MAS by 3.6% in well-trained runners. Therefore, sufficient stimulus around VO_{2max} (or speed—MAS) is necessary to improve this parameter. At the same time, it seems that the higher the athlete's performance level, the less margin for improvement in VO_{2max}, although the associated speed (MAS) may increase. However, it seems that a certain volume of training at these high intensities, along with sufficient volume at moderate intensities (z2), improved the absolute speed of VT_1 and VT_2 and the percentage of VT_1 relative to VO_{2max}, leading, in turn, to a rightward shift (high intensity) in these thresholds.

Regarding biomechanical parameters, our study did not show significant changes at moderate or high speeds after the regular training period. In that sense, a recent study [21] found an increase of 3% in CT at submaximal speeds in recreational runners and an improvement of 5% in recreational and trained runners after 8 weeks of an endurance training program. However, they did not see changes in the biomechanics of trained runners. Another study [41] observed an increase in RE without biomechanical changes associated with a period of continuous method training. This may be because biomechanical changes at the intensities at which RE is usually assessed (submaximal intensities) require more time to alter. In addition, optimal performance may require the optimization of running biomechanics beyond simply minimizing energy costs [15]. Although multiple studies have investigated the association between running biomechanics and RE, the evidence is often inconclusive or even conflicting [15]. For example, it is well known that step length has a significant effect on running economy, and most people self-select a step length that is optimal in terms of RE [12]. However, for CT, Tam et al. [43] suggest that reducing velocity loss during ground contact is more crucial than CT itself, while Barnes and Kilding [16] claim that a shorter CT during the stance phase enables a quicker transition from the braking phase to the swing phase [16]. In addition, a lower vertical displacement and higher K_{leg} have shown significant associations with better RE [15].

4.1. Practical Applications

Based on these findings, we recommend that coaches take into consideration the objectives of their planning. If RE is to be improved, it is not necessary to include an excessive training volume at high intensities. However, if the aim is to improve maximal aerobic speed and its physiological components, a training plan like the one proposed in this study may be effective. In addition, tracking cardiometabolic parameters appears to be more crucial than evaluating mechanical parameters. Although this study involved long-distance runners, the outcomes could apply to other sports involving running such as field sports.

4.2. Limitations

This study has several limitations. The first was that the RE tests between runners were conducted using absolute running speed and did not ensure a similar relative intensity for all runners. Secondly, for the maximal speed condition, we evaluated the spatiotemporal parameters of the gait based on a one-min timeframe, which might not be enough to adjust the running kinematics to the running speed. This may have caused the kinematics of the athletes not to have adapted to the running speed. In addition, the participants were males and females, but we only analyzed one group because the female group was very small. However, a previous analysis showed no influence of sex on the results obtained. Finally, we did not incorporate a control group to compare our participants. Therefore, the results of this study should be interpreted with caution.

5. Conclusions

The effects of 20 weeks of a regular endurance and strength training program produced a deterioration of 3.5% in RE without spatiotemporal changes at submaximal speed. Contrary, we found an improvement of 4.6% in relative VO_{2max} and 2.8% in MAS. The speed associated with VT_1 and VT_2 increased with the training program. There was an increase in VT_1 relative to MAS but not in VT_2. In this study, the spatiotemporal parameters remained unchanged with the training program. This suggests that a long endurance training program could improve performance and physiological factors without changing the biomechanics of runners.

Author Contributions: All authors contributed significantly to this manuscript's final version and the interpretation of the results. S.R.-B., B.V., V.M.d.l.C. and F.G.-M. conceived and planned the experiments. S.R.-B. and V.M.d.l.C. carried out the experiments. D.J.S.-G. and J.M.G.-R. contributed to sample preparation. S.R.-B. took the initiative to write the manuscript, which was completed by V.M.d.l.C., B.V., F.G.-M., D.J.S.-G. and J.M.G.-R. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the "Comité de ética de la investigación clínica con medicamentos" on 30 November 2022 (CEIC924).

Informed Consent Statement: Informed consent was obtained from all subjects involved in this study in order to publish this paper.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

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