

Transfer of strength training to running mechanics, energetics, and efficiency

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ABSTRACT: To examine the effects of increased strength on mechanical work, the metabolic cost of transport (Cost), and mechanical efficiency (ME) during running. Fourteen physically active men (22.0 ± 2.0 years, 79.3 ± 11.1 kg) were randomized to a strength-training group (SG, $n = 7$), who participated in a maximal strength training protocol lasting 8 weeks, and a control group (CG, $n = 7$), which did not perform any training intervention. Metabolic and kinematic data were collected simultaneously while running at a constant speed ($2.78 \text{ m}\cdot\text{s}^{-1}$). The ME was defined as the ratio between mechanical power (P_{mec}) and metabolic power (P_{met}). The repeated measures two-way ANOVA did not show any significant interaction between groups, despite some large effect sizes (d): internal work (W_{intr} , $p = 0.265$, $d = -1.37$), external work (W_{extr} , $p = 0.888$, $d = 0.21$), total work (W_{tot} , $p = 0.931$, $d = -0.17$), P_{mec} ($p = 0.917$, $d = -0.17$), step length (SL, $p = 0.941$, $d = 0.24$), step frequency (SF, $p = 0.814$, $d = -0.18$), contact time (CT, $p = 0.120$, $d = -0.79$), aerial time (AT, $p = 0.266$, $d = 1.12$), P_{met} ($p = 0.088$, $d = 0.85$), and ME ($p = 0.329$, $d = 0.54$). The exception was a significant decrease in Cost ($p = 0.047$, $d = 0.84$) in SG. The paired t-test and Wilcoxon test only detected intragroup differences (pre- vs. post-training) for SG, showing a higher CT ($p = 0.041$), and a lower Cost ($p = 0.003$) and P_{met} ($p = 0.004$). The results indicate that improved neuromuscular factors related to strength training may be responsible for the higher metabolic economy of running after 8 weeks of intervention. However, this process was unable to alter running mechanics in order to indicate a significant improvement in ME.

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INTRODUCTION

Strength training is traditionally considered a method for increasing muscular performance in anaerobic exercise. Many of the benefits of strength training, however, can also be transferred to the biomechanics and bioenergetics of running. These benefits work in parallel to produce the same mechanical output while optimizing the body's expenditure of metabolic energy [1]. The mechanical work to accelerate and elevate the body centre of mass (BCoM) with respect to the external environment is known as external work (W_{ext}) while the work required to accelerate the limbs relative to the BCoM is known as internal work (W_{int}) [2]. The sum of W_{ext} and W_{int} expresses the total mechanical work (W_{tot}) done by the body [2]. The

net amount of metabolic energy in joules (J) required from the locomotor system to move one kilogram (kg) of body mass one meter (m) is defined as the cost of transport (Cost; $\text{J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$) [3]. Using W_{tot} and Cost, it is possible to calculate mechanical efficiency (ME) according to the equation of Cavagna and Kaneko [1]:

$$ME = W_{\text{tot}}/\text{Cost}$$

While Cost is a measurement of the energetic expenditure from a metabolic perspective, its inverse ($1/\text{Cost}$) describes how efficient a person can move [4]. Assuming that W_{tot} remains unchanged, as Cost increases, ME decreases. It is possible, however, that W_{tot}

and Cost may increase concomitantly. In this case, a similar ME will be maintained even with an increased Cost. Because of this intricate interplay between ME, W_{tot} , and Cost, it is important understand how each parameter is affected by strength training. Changes in running parameters after strength training have been investigated both from the biomechanical (W_{tot}) perspective and from the bioenergetics (Cost) perspective [5–8]. Yet, there are no studies which can clarify how strength training affects the two simultaneously (ME).

In practice, a strengthened body may consume less oxygen at determined speeds [9, 10]. Internally, strength training can optimize neuromuscular factors by improving the firing rate and synchronization of the motor unit, as well as the oxidative characteristics of type II fibres, and anaerobic enzyme activity [11, 12]. Due to the predominance of neuromuscular adaptations in the first weeks of strength training, a similar mechanical output (W_{tot}) is expected. In addition, short-term training (8 weeks) would not be sufficient to cause peripheral body changes such as muscular hypertrophy [10, 12], further emphasizing the ability of the neuromuscular system to produce force during running.

This may also be accompanied by changes in kinematic parameters, such as lower contact time (CT) (and higher aerial time (AT)) and lower step frequency (SF) (and longer step length (SL)). While not the same as directly measuring the mechanical work of locomotion, these parameters are strongly correlated with a subject's mechanical energy profile when moving at a constant speed [4, 13].

Studies of ME have highlighted the significant role of the elastic component of the muscle tendon unit (MTU) during the eccentric contractions performed during every step [1, 14, 15]. The MTU acts as a passive energy store and releases elastic energy back to the system to increase efficiency during running [16]. Several authors have proposed a strength training routine to runners which aims to optimize the stretch-shortening cycle (influencing the bouncing stiffness of the running) [5, 7, 17]. Accordingly, the stiffness of the “spring” would increase, improving the capability of the MTU to deform and release elastic energy without any additional cost to the system. This would result in a higher W_{tot} accompanied by a similar Cost, increasing the ME values [4]. It is, furthermore, worth noting

that athletes require less metabolic energy than sedentary individuals to produce similar mechanical work, resulting in higher ME [4, 15]. This difference between sedentary and trained individuals can be referred to as the ‘deficit effect’. Moore [18] has shown that the initial fitness level of participants is particularly crucial for training studies concerned with improving aerobic fitness. The ‘deficit effect’ may influence the trainability of the Cost. Therefore, we proposed a strength training programme for physically active young participants to verify its influence on the ME. Subsequently, our second aim was to explore how these adaptations impact the mechanical (P_{mec} and W_{tot}) and metabolic (P_{met} and Cost) partitioning of ME during running. We hypothesized that the ME might increase due to lower Cost values (metabolic counterpart) accompanied by maintenance of W_{tot} (mechanical counterpart). Understanding the relationship between strength training and ME can offer valuable insight into sedentary individuals’ activity and health.

MATERIALS AND METHODS

Participants

The baseline characteristics of the participants are shown in Table 1. Participants were allocated to two different groups by simple randomization (flipping a coin). A result of ‘heads’ represented the Strength training group (SG, $n = 7$), and the ‘tails’ side, the Control group (CG, $n = 7$). The researcher that conducted the allocation was not involved with the study to maintain the confidentiality of the process and blinding of the data processing. At the baseline, the two groups did not show any different physical characteristics (Table 1). Subjects were not permitted to participate in any regular training programme for at least six months prior to the experiments. All participants were physically healthy, but did not partake in regular physical activity (≤ 2 times per week). During the training period, individuals in the CG did not perform any additional physical training. All participants volunteered to participate in this study. No participant had any previous experience in strength training or treadmill testing. All participants were informed of the risks and benefits of the study, and read and signed a free and informed consent form before their participation.

TABLE 1. Anthropometric data for age, height, body mass, and body fat for strength training (SG) and control groups (CG).

| | Pre-training | | Post-training | |
|--------------------|--------------|-------------|---------------|-------------|
| | SG (n = 7) | CG (n = 7) | SG (n = 7) | CG (n = 7) |
| Age (years) | 22.0 ± 2.3 | 22.0 ± 1.8 | - | - |
| Body Mass (kg) | 77.0 ± 14.1 | 79.7 ± 7.4 | 76.7 ± 12.2 | 80.0 ± 7.7 |
| Body Mass Index | 24.4 ± 4.2 | 23.8 ± 1.6 | 23.3 ± 1.1 | 24.1 ± 1.6 |
| Body Fat (%) | 17.5 ± 5.2 | 16.0 ± 5.1 | 17.4 ± 4.3 | 16.9 ± 5.6 |
| Thigh Diameter (m) | 0.53 ± 0.05 | 0.55 ± 0.04 | 0.56 ± 0.04 | 0.55 ± 0.03 |
| Leg Diameter (m) | 0.38 ± 0.02 | 0.40 ± 0.03 | 0.38 ± 0.02 | 0.39 ± 0.04 |

Values are $\bar{x} \pm SD$.

Design and Procedures

The metabolic assessment consisted of the oxygen uptake analysis, in which P_{met} was considered the average oxygen uptake by the time analysed. In this line, the ratio between P_{met} and the running speed performed ($2.78 \text{ m}\cdot\text{s}^{-1}$) defined Cost. Mechanical power (P_{mec}) was measured by calculating the mechanical energy fluctuations of both whole-body BCoM and the segmental centres of mass. The biomechanical variables calculated were SF, SL, CT, AT, W_{int} , W_{ext} , and W_{tot} . The total study period lasted ten weeks, during which individuals were evaluated before and after the training programme.

During the preliminary visit, individuals were familiarized with equipment and protocols. In the following step, we assessed body mass, height, and skinfold thickness for the body composition calculation. The treadmill running and maximal strength tests were performed one week before and one week after the training protocol, separated by 48–72 hours. One-repetition maximum (1-RM) tests were performed on two different days paired by multi-mono articular and upper-lower limb groups. The participants also underwent one test of maximal strength during the 4th week of the training period.

Body Composition

An electronic scale (resolution 0.1 kg, Filizola, São Paulo, Brazil) and a stadiometer (resolution 1mm, Filizola, São Paulo, Brazil) were used to evaluate body mass and height, respectively. Body composition was assessed using the skinfold technique. The measurements of skinfold thickness were performed on the right side of the subject's body with a calibrated skinfold caliper (Cescorf, São Paulo, Brazil). The sites included the triceps, subscapular, biceps, supraspinatus, abdominal, front thigh and medial calf. A seven-site skinfold equation was used to estimate body density [19], and body fat calculated using the Siri [20] equation.

Maximal Dynamic Force Test

Before the maximal dynamic force test, the participants performed two or three contractions to warm up. We tested the 1-RM force on three separate days paired with squat and pull down (day 1); leg-press and plantar flexion (day 2); bench press, knee extension and knee flexion (day 3). We decided to show 1-RM values only for squat and leg exercises due to the significant lower limb contribution during running. In all tests, every participant was verbally encouraged to achieve their best performance. After each repetition, the load increased until the participant was unable to perform the required movement. The last complete extension with the highest possible weight determined the 1-RM value.

Submaximal Running Test

Metabolic Measurements

The submaximal running test was performed on a treadmill (BH Fitness Explorer ProAction, Vitoria-Gasteiz, AL, Spain). Prior to testing, the participant remained in the orthostatic position for the de-

termination of baseline standing oxygen consumption. The average values measured in the last 3 minutes determined the mean baseline standing oxygen consumption (P_{met} -baseline).

Each participant began the warm-up at $1.39 \text{ m}\cdot\text{s}^{-1}$, and the speed was increased by $0.28 \text{ m}\cdot\text{s}^{-1}$ each min until the speed reached $2.78 \text{ m}\cdot\text{s}^{-1}$. This speed was kept constant for six minutes. The heart rate (Polar, Kempele, Finland), end-tidal partial pressure of oxygen, end-tidal partial pressure of carbon dioxide, oxygen uptake, carbon dioxide output and ventilation rate (VO2000, Inbramed, Saint Paul, USA) were measured continuously. The sampling rate of the collected values was once every 10 s, and the data were acquired using the Aerograph software (Inbramed, Saint Paul, USA). Participants were instructed to avoid ingesting stimulants and to not practise strenuous exercise at least 24 hours prior to the test. The running speed of $2.78 \text{ m}\cdot\text{s}^{-1}$ was considered a submaximal speed according to Hreljac et al. [21] and Steudel-Numbers et al. [22], and reported to be comfortable due to its proximity to the speed of transition between walking and running. This speed also ensures that the subject is able to exercise aerobically and sustain the pace for the 6 minutes required without becoming fatigued.

During running, the mean value for oxygen consumption was obtained from the data collected between the 4th and 6th minute. The mean net oxygen consumed during exercise was defined as P_{met} . This value in $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ was multiplied by an energetic equivalent of $20.9 \text{ J}\cdot\text{ml}^{-1}$ [3] and, divided by 60 s, indicating the value of P_{met} in $\text{W}\cdot\text{kg}^{-1}$. The Cost was determined by subtracting P_{met} from P_{met} -baseline, divided by speed, and expressed in $\text{J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$.

Mechanical Measurements

The biomechanical data collection was performed concurrently with metabolic data measurements. The kinematic data were collected by one camera (IMPERX Kardon-CL 210, Boca Raton, FL, USA) using a motion analysis system (SPICA, Hollis, NH, USA), with a sampling frequency of 200 Hz. The camera and tripod were positioned perpendicular to the treadmill at a distance of 4 meters to avoid any parallax error. Passive reflective markers were placed over the fifth metatarsal, calcaneus, lateral malleolus, femoral epicondyle, greater trochanter, acromion, lateral epicondyle of humerus, middle point ulnar-radius, and temporal head. A sample of 20 steps between the 4th and 6th minute was analysed (Dvideow, Campinas, Brazil). Mathematical routines were created in MATLAB 5.3 software (MathWorks Inc., Natick, USA) to determine the magnitudes of the biomechanical parameters. The inverse of the stride time (product between the frame numbers digitalized and time variation of each frame, 0.005 s) provided SF. The SL values resulted from the quotient between horizontal speed ($2.78 \text{ m}\cdot\text{s}^{-1}$) and SF. The CT was defined as the average time during foot contact on the treadmill. The AT was represented as the time that neither of the feet were in contact with the ground. We used low-pass filtering defined by the residual analysis, which automatically selects optimal filter cut-off frequencies for each marker in the x, y and z directions [23].

Since the data position for each segment is known, W_{tot} can be calculated as the sum of W_{ext} and W_{int} , in which the W_{ext} was calculated according to König's theorem [2] and W_{int} estimated by Minetti's equation [24]. The P_{mec} was then calculated by multiplying the W_{tot} and horizontal velocity. The ME was expressed as the ratio between P_{mec} and P_{met} . [1].

Strength Training

The supervised, 8-week strength training was carried out twice per week. Between the sessions, there was a minimal interval of 48 hours. Each training session included 45° leg press, squat, knee extension, knee flexion, and plantar flexion. All participants performed three familiarization sessions with submaximal loads. After that, the participants performed the test of 1-RM for each exercise. The participants initially performed a submaximal warm up and after 5 min of rest, a maximal test for each exercise. A total of 5 trials were available to achieve the 1-RM. All attempts were performed with 2-second concentric and eccentric actions controlled using an electronic metronome (KORG, Melville, NY, USA). The recovery interval between the trials was 5 minutes. The test-retest reliability coefficient (intra-class correlation coefficient [ICC]) was 0.85–0.98 for RM_{leg} and RM_{squat} , respectively.

The total load volume was increased according to the percentage of 1-RM. Each training session began with a warm-up series of ten repetitions for 50% of the load used for the session. Following the initial adjustment period, the maximal intensity during the first four

TABLE 2. Volume (sets and reps) and intensity (percentage of one repetition maximal (% 1 RM)) in each period (weeks) of the training program.

| Weeks | Sets | Reps | %1-RM |
|-------|------|------|-------|
| 1 | 1 | 20 | 60 |
| 2 | 2 | 15 | 70 |
| 3 | 3 | 10 | 75 |
| 4 | 4 | 10 | 80 |
| 5 | 3 | 6 | 85 |
| 6 | 4 | 6 | 85 |
| 7 | 4 | 6 | 90 |
| 8 | 4 | 6 | 90 |

weeks was 80% of 1-RM [12]. Table 2 shows the periodization of training (volume vs intensity) adopted in the present study.

Statistical Analysis

All data are presented as means (\bar{x}) and standard deviations (SD). The data normality was tested using the Shapiro-Wilk test. The repeated measures two-way ANOVA (factors: time and group) test was performed to identify interaction between the two different periods (before and after the 8-week training programme). In parallel, paired t-tests were applied to compare intragroup variables before and after training. When the normality test failed (for SF, SL, and CT), the

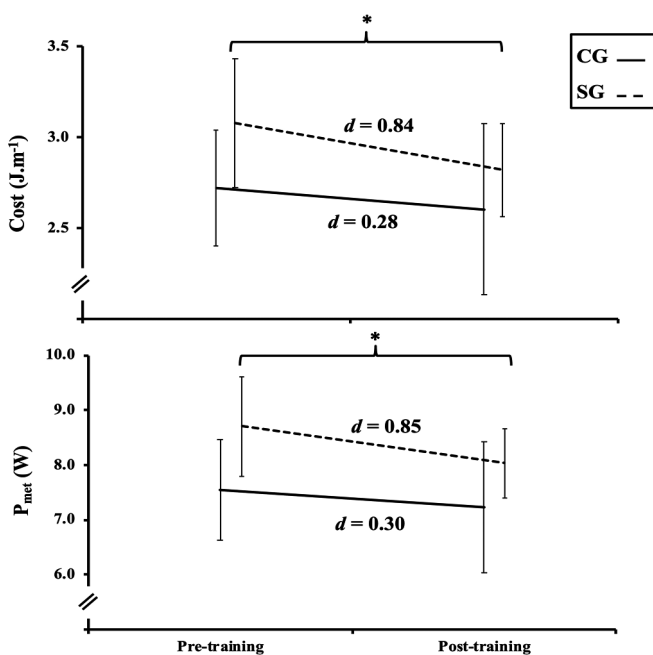


FIG. 1. Interaction effects (*) and effect sizes (d) among the cost of transport (Cost, upper panel), and metabolic power (P_{met} , lower panel), on pre- and post- training in strength training group (SG) and control training group (CG). Cost (* $p = 0.003$); Pmet (* $p = 0.004$).

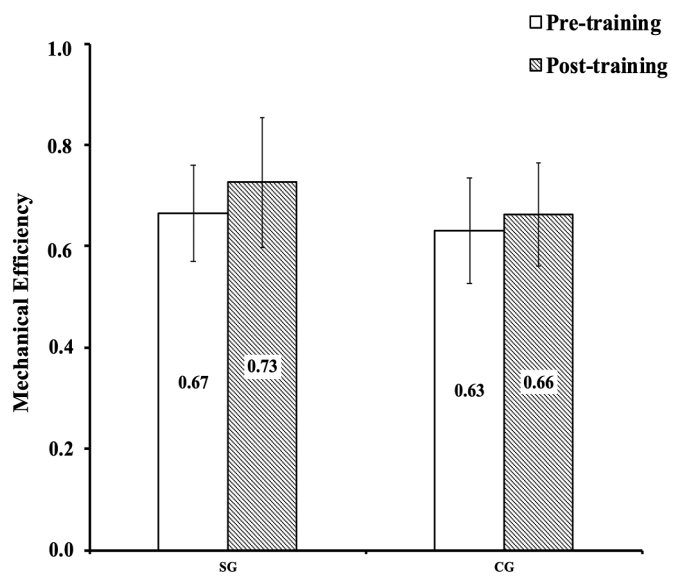


FIG. 2. Change in mechanical efficiency (ME) at pre- and post-training periods in control (CG) and strength training (SG) groups. Effect size (d) in SG and CG was 0.54 and 0.14, respectively.

Wilcoxon test was performed. The effect size (*d*) was calculated, according to Cohen [25] regarding two dependent groups for all measurements. The reliability of body measurements and RM tests was controlled by intraclass correlation coefficient (ICC) tests. Statistical power was calculated using G*Power software through computing and achieving post-hoc analysis and was determined to be from 0.7 and 0.9. These values were relevant to primary outcomes of the study such as Cost, P_{met} , and ME for the sample sizes used at the 0.05 alpha level ($n = 14$). Moreover, studies with a similar design [6, 8] have used a sample size equivalent to that of our investigation ($n = 11$ and $n = 15$, respectively) with significative outcomes due to the related power utilized. All statistical procedures were performed using SPSS software (version 23.0).

Ethics

All procedures adhered to the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Declaration of Helsinki of 1975, as revised in 2008. The Ethics Committee of the Federal University of Rio Grande do Sul, Brazil approved the present study (number 18770) according to the Declaration of Helsinki.

RESULTS

The two-way repeated-measures ANOVA test did not show a significant interaction between SG and CG after eight weeks of strength training for ME ($p = 0.329$) despite the ‘medium’ effect size (*d*) presented by SG after the training period ($d = -0.54$) (Figure 1).

Both maximal dynamic force parameters, RM_{leg} and RM_{squat} , increased for SG ($p = 0.002$, and $p < 0.001$, respectively), followed by a ‘large’ effect size ($d = -1.19$, $d = -0.95$), whereas CG remained constant ($p = 0.813$, and $p = 0.393$) (Table 3).

The biomechanical variables represented by P_{mec} and its components, W_{tot} , W_{int} and W_{ext} , showed no significant differences ($p = 0.917$, $p = 0.931$, $p = 0.888$, $p = 0.265$, respectively) between pre- and post-strength training values, accompanied by a ‘small’ effect size ($d < |0.5|$), with the exception of a ‘large’ effect size for W_{int} ($d = -1.37$) (Table 4). Moreover, spatiotemporal variables (SL, SF, CT, and AT) did not show any significant ‘time vs group’ interaction ($p = 0.941$, $p = 0.814$, $p = 0.120$, $p = 0.266$, respectively). These results agree with the ‘small’ effect size presented by SL and SF ($d = 0.24$, and $d = -0.18$, respectively). Conversely, the CT and AT showed a ‘medium’ and ‘large’ effect size ($d = -0.79$, and $d = 1.12$, respectively) (Table 4). Both P_{met} and Cost decreased after strength

TABLE 3. Repetition maximal tests by Squat and Leg Press exercises for strength training (SG) and control groups (CG).

| | Pre-training | | Post-training | |
|---------------------------|--------------|--------------|---------------|--------------|
| | SG (n = 7) | CG (n = 7) | SG (n = 7) | CG (n = 7) |
| Squat (kg) | 104.4 ± 38.3 | 132 ± 24.9 | 146.2 ± 49.3* | 132 ± 24.6 |
| Leg Press 45° (kg) | 184.5 ± 73.9 | 248.0 ± 40.3 | 276.0 ± 79.8* | 248.6 ± 40.9 |

Values are $\bar{x} \pm SD$. The asterisk indicates significant differences between pre and post-training for each exercise ($p = 0.001$).

TABLE 4. Mechanical (W_{int} , W_{ext} , W_{tot} and P_{mec}) e spatiotemporal (SL, SF, CT and AT) parameters measured during the treadmill running submaximal test, before and after 8 weeks in the strength training (SG) and control group (CG).

| | | SG (n = 7) | CG (n = 7) | SG (n = 7) | CG (n = 7) | <i>p</i> | <i>p</i> | <i>d</i> | <i>d</i> |
|----------------|--|--------------|--------------|---------------|--------------|-----------------|------------------|----------|----------|
| | | Pre-training | | Post-training | | (time vs group) | (intra-group) SG | SG | CG |
| Mechanical | W_{int} (J·kg⁻¹·m⁻¹) | 0.47 ± 0.07 | 0.49 ± 0.05 | 0.54 ± 0.03 | 0.51 ± 0.04 | 0.265 | 0.073 | -1.37 | -0.53 |
| | W_{ext} (J·kg⁻¹·m⁻¹) | 1.48 ± 0.17 | 1.37 ± 0.30 | 1.43 ± 0.27 | 1.24 ± 0.28 | 0.888 | 0.567 | 0.21 | 0.47 |
| | W_{tot} (J·kg⁻¹·m⁻¹) | 1.93 ± 0.22 | 1.85 ± 0.27 | 1.97 ± 0.26 | 1.75 ± 0.25 | 0.931 | 0.932 | -0.17 | 0.37 |
| | P_{mec} (W·kg⁻¹) | 5.37 ± 0.62 | 5.13 ± 0.75 | 5.49 ± 0.72 | 4.87 ± 0.70 | 0.917 | 0.947 | -0.17 | 0.36 |
| Spatiotemporal | SL* (m) | 1.13 ± 0.18 | 1.09 ± 0.06 | 1.09 ± 0.07 | 1.08 ± 0.05 | 0.941 | 0.237 | 0.24 | 0.20 |
| | SF* (Hz) | 2.46 ± 0.58 | 2.54 ± 0.15 | 2.54 ± 0.18 | 2.57 ± 0.13 | 0.812 | 0.237 | -0.18 | -0.19 |
| | CT* (s) | 0.298 ± 0.04 | 0.273 ± 0.01 | 0.325 ± 0.02 | 0.297 ± 0.01 | 0.120 | 0.041# | -0.79 | -1.94 |
| | AT (s) | 0.116 ± 0.05 | 0.104 ± 0.02 | 0.073 ± 0.02 | 0.092 ± 0.02 | 0.266 | 0.088 | 1.12 | 0.58 |

Values are means ± SD. *P* values are subdivided by parametric e non-parametric variables (*) and effect size (*d*) was calculated for each group. W_{int} , internal mechanical work; W_{ext} , external mechanical work; W_{tot} , total mechanical work; SL, step length; SF, step frequency; CT, contact time; AT, aerial time. The symbol (#) indicates significant difference.

training for SG ($p = 0.004$, and $p = 0.003$, respectively) with a 'large' effect size ($d = 0.85$, $d = 0.84$, respectively) (Figure 2, A-B).

DISCUSSION

We aimed to quantify the effects of 8 weeks of maximal strength training on the ME of running in healthy young men. Our results indicate that enhanced muscle strength improved the metabolic economy (lower Cost and P_{met}) during running while W_{tot} and ME remained unchanged (Figure 2). Consequently, muscle force improvement (demonstrated in the 1-RM of SG) and the metabolic economy of running seem to be related to neuromuscular adaptations associated with the early stages of maximal strength training [11].

As discussed in recent literature, muscle strength appears to interact with Cost in a dose-dependent manner [6, 26]. Whereas 1-RM increased around 40% in the SG, Mikkola *et al.* [26] reported much smaller gains (3.6%) than in the present study with no improvements in Cost. Meanwhile, our 1-RM results were similar, even superior, compared to those of Millet *et al.* [6] and Støren *et al.* [10] (23–33%), who reported significant improvements in Cost. As the training period was considered short for SG (only 8 weeks), neuromuscular adaptations are likely the main factor responsible for increasing force which can be transferred to running without an 'extra cost' [7]. Although speculative, our results suggest that the changes in the metabolic economy could have a different physiological origin. Notably, improvements in Cost for healthy young individuals could be partly the result of improved 'motor' function (oxidative function and neural control) rather than an improvement in the 'machine'/structural function (limb, lever system) [4]. For instance, Moore [18] reported that kinematics, kinetics, spatiotemporal and neuromuscular factors are related to an economical running technique. Our results support the idea that neuromuscular adaptations due to the early stages of strength training could be related to reduced energy expenditure in physically active individuals. The lack of change in thigh diameter supports the theory of neuromuscular predominance under effects of maximal strength training after 8 weeks as opposed to hypertrophic adaptations. Further studies involving an extended period of strength training in participants not regularly trained and the muscle activation during the propulsion phase and the agonist-antagonist co-contraction could check this rationale and refine the mechanisms related to biomechanical factors affecting the metabolic cost of running.

We did not observe any significant differences in running mechanics between pre- and post- strength training measurements. The lack of significant changes in kinematic variables is in agreement with the lack of significant changes in musculature and body composition (e.g., thigh diameter ~ 0.53 to ~ 0.56 m, Table 1). According to this, Millet *et al.* [6] reported that maximal strength training did not influence the running spatiotemporal parameters in triathletes, corroborating our findings and the likely neuromuscular optimization during each step cycle of running. This behaviour is based on applying less force concerning the maximal strength,

sustaining the maintenance of kinematic variables. This inference would be reasonable since it is known that there is an inverse correlation between the sum of horizontal and vertical peak forces with running economy ($R = -0.71$) [27]. It may indicate an increased force applied during ground contact, whereas the cost to activate the muscles remains the same for equal intensity [28].

Similar to the current study that sought to find possible differences in running biomechanics due to gains in muscular strength, Cavagna *et al.* [29] reported lower W_{ext} and higher W_{int} values in older adults compared to young people. Tracing a parallel due to the higher muscular strength of younger people (around 90% stronger) [30], these biomechanical strategies found in the older group were crucial to saving metabolic energy. In this case, a higher W_{int} was necessary to ensure that "weaker runners" would run at the same speed as the younger group. Despite the primary attention being given to the lower limbs during the strength training, in accordance with Cavagna and Kaneko [1], who reported lower limbs as responsible for about 80–90% of the W_{int} done during running (larger oscillations), strength training did not significantly affect running biomechanics. Such a result could express a neuromuscular economy acting on the SG, decreasing its energy expenditure.

P_{mec} did not change in SG ($p = 0.91$). Therefore, the change in metabolic expenditure was not enough to cause a significant improvement in ME. The non-significant increase in the ME for SG (from 0.67 to 0.73, pre-to-post training; effect size (d) = 0.54) coincides with similar research specifically focused on running at this speed [31, 32]. Further, the maintenance of P_{mec} and ME indicates an unaltered capacity of the body to store elastic energy during the step [1, 4] in physically active individuals. These modifications are likely not demonstrated in our physically active participants due to training specificity (lower speed and maximal force) or because of the low running speed ($2.78 \text{ m}\cdot\text{s}^{-1}$) [4, 13].

The present investigation has limitations regarding the small sample size, which consequently led to low statistical power in finding significant differences amongst SG and CG (see details in Methods section). Nevertheless, although there were no significant differences in P_{mec} or ME between CG and SG, a significant interaction was still found in SG between Cost and P_{met} . Still, the absence of variables representing the actual 'spring-mass' model (calculated by dynamometric assessment) also precluded assessing the musculo-tendinous system and its energy-saving mechanism [13].

These results agree with previous studies reporting the effects of strength training without concomitant endurance training [9, 33–35]. In common with our results, the better aerobic capacity elicited by strength training also indicated a significantly large percentage change tending to type II muscle fibres [35] and its area [33], rather than a better anaerobic capacity [9] and a higher average of muscular electrical activity during the first 500 ms of the rapid isometric action [33]. In relation to elastic energy, although ME represents the possibility to store and return elastic energy in the muscle-tendon units of lower limbs, direct evidence is necessary to determine the

real function of these structures in submaximal running after muscle strength training [36].

CONCLUSIONS

Eight weeks of conventional strength training did not significantly affect the running biomechanics in sedentary individuals. Accordingly, Cost diminished while P_{mec} and ME remained unchanged, indicating a better movement economy due to strength training adaptations. These adjustments are likely due to an improvement in the effectiveness of motoneuron recruitment developed during strength training exercises and transferred to running activity.

Given the complex combination of strength and endurance training regarding each activity's load control, and the difficulty in critical situations to apply both training sections contemporarily, this investigation supports coaches and practitioners including a strength train-

ing routine to promote the running metabolic progression through movement economy.

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Conflict of interest

None of the authors have any conflict of interest regarding this work.

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