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The Relationship Between Running Economy and Biomechanical Variables in Distance Runners

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In this study, we analyzed the relationship between running economy (RE) and biomechanical parameters in a group running at the same relative intensity and same absolute velocity. Sixteen homogeneous male long-distance runners performed a test to determine RE at 4.4 m.s^{1}, corresponding to 11.1% below velocity at the ventilatory threshold. We found significant correlations between RE and biomechanical variables (vertical oscillation of the center of mass, stride frequency, stride length, balance time, relative stride length, range of elbow motion, internal knee, ankle angles at foot strike, and electromyographic activity of the semitendinosus and rectus femoris muscles). In conclusion, changes in running technique can influence RE and lead to improved running performance.

Key words: electromyography, kinematics, locomotion, oxygen uptake

Running economy (RE) is typically defined as the energy required to run submaximally at a given velocity and is determined by measuring steady-state oxygen consumption (VO_2) and the respiratory exchange ratio. Considering body mass when running at the same velocity, runners with good RE spend less energy and, therefore, less oxygen than runners with poor RE (Saunders, Pyne, Telford, & Hawley, 2004). A number of factors (Saunders, Pyne, Telford, & Hawley, 2004) and interventions (i.e., training, motor learning, nutrition strategies) appear to influence RE in highly trained or elite runners (Di Prampero, Atchou, Bruckner, & Moia, 1986; Hausswirth & Brisswalter, 2008).

RE performance during long-distance running has been studied extensively, and results suggest it is an important factor in explaining performance in long-distance events (Conley & Krahenbuhl, 1980; Di Prampero et al., 1986; Di Prampero, 1986; Sawyer et al., 2010). In these studies, RE was recorded during a submaximal intensity exercise performed by runners at the same relative intensity (expressed in percent of velocities reached with maximal oxygen uptake [VO_2max] or corresponding to the ventilatory threshold [VT]). However, these relative velocities represent different absolute running velocities and, thus, distinct levels of mechanical demand.

On the other hand, a second approach sought to relate RE changes with biomechanical parameters, such as the temporal or spatial characteristics of the running pattern (Williams & Cavanagh, 1987), ground reaction force (Nummela, Keranen, & Mikkelsson, 2007; Nummela, Rusko, & Mero, 1994), capacity to store and return elastic energy (Gleim, Stachenfeld, & Nicholas, 1990), or total mechanical work (Mian, Thom, Ardigo, Narici, & Minetti, 2006; Minetti, Ardigo, & Saibene, 1994). In all these studies, RE was recorded for all runners at the same

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absolute running velocity, although it would correspond to different physiological intensities and, thus, distinct levels of metabolic demand. Although several studies analyzed the relationship between RE and biomechanical parameters, the results were contradictory, and few studies found a significant relationship between the kinematic variables, muscle activity in the lower limbs, and RE in long-distance runners (Cavanagh, Pollock, & Landa, 1977; Cavanagh & Williams, 1982; Kyrolainen, Belli, & Komi, 2001).

By analyzing the relationship between RE and the mechanical and neuromuscular variables in participants running at the same velocity, as well as the increased electromyographic signal (EMG) of the working muscles and associated increase in power output, it may be possible to partly explain the variation in energy expenditure (Kyrolainen et al., 2001) that may account for up to 30% of performance in distance runners (Conley & Krahenbuhl, 1980; Saunders, Pyne, Telford, & Hawley, 2004). The increased fractional use of VO_2max is immediately accompanied by an increase in amplitude of the electromyographic signal; therefore, the different relative intensities may account for this relationship.

Analyzing within-participant effects, Cavanagh and Williams (1982) found submaximal oxygen uptake (VO_2submax) increased curvilinearly as stride length either lengthened or shortened from what the runner self-selected. They concluded there is little need to dictate stride length for well trained athletes, as they display near optimal stride length. However, when analyzed between participants, velocity directly influences kinematic parameters. For instance, Cavanagh et al. (1977) found that elite runners showed less vertical oscillation, were more symmetrical, and had better RE. On the other hand, Kyrolainen et al. (2000) reported that some biomechanical parameters (angular velocities and ankle, knee, and hip joint displacements) were not good predictors of RE. Again, athletes performed the tests at the same speeds but at different physiological intensities. Therefore, to achieve a better understanding of the variables involved in long-distance running performance, we analyzed the relationship between RE and biomechanical variables in experienced distance runners, who ran at the same absolute velocity with similar physiological intensity.

Method

Participants

The study sample comprised 16 healthy male volunteers. All were long-distance runners and members of the Athletic Federation of Rio Grande do Sul–Brazil, with times between 30 and 36 min achieved in national competitions (10,000 m) 2–5 weeks prior to the evaluation period, with similar speeds at the VT (verified in an incremental treadmill running protocol), and who were free of nutritional restrictions. Participant characteristics were (*M* age = 27 years, *SD* = 5.7; *M* body mass = 64.5 kg, *SD* = 5.8; *M* height = 1.74 m, *SD* = 0.08; *M* leg length = 0.82 m, *SD* = 0.04; *M* body density = 1.08 $g.ml^{-1}$, *SD* = 0.01; *M* body fat = 9.11%, *SD* = 1.48; *M* training volume = 66.8 $km.week^{-1}$, *SD* = 13.6; *M* experience = 7.7 years, *SD* = 3.2; and *M* VO_2max in treadmill running = 56.36 $ml.kg^{-1}.min^{-1}$, *SD* = 4.7). Prior to giving their written consent to participate, all participants were fully informed of the purpose, nature, practical details, and possible risks associated with the experiment, as well as their right to terminate participation at will. The institution's Research Ethics Committee approved the present study according to the Declaration of Helsinki.

Experimental Design

Participants took part in two experimental sessions (see Figure 1) at 2-week intervals. They wore their own spikeless training shoes. The ambient temperature (25°C) and relative humidity (53%) were controlled according to ISO-8573-1 (International Standards).

Preliminary Test. First, anthropometric parameters were recorded (body mass, height, and leg length), using scales and a stadiometer (FILIZOLA, São Paulo, Brazil). The percentage of body fat was calculated using the Siri equation (1993). Body density was calculated using the Jackson and Pollock equation (1978). All athletes performed a treadmill running familiarization session with specific ergospirometric accessories.

Incremental Treadmill Running Protocol. After a brief warm-up and 10-min rest (5 min sitting and 5 min standing), participants performed a progressive protocol with an initial velocity of 2.7 $m.s^{-1}$, in which speed was increased by 0.27 $m.s^{-1}$ at 1-min intervals and treadmill incline was fixed at 1% (Peyré-Tartaruga et al., 2009). Load increments were calculated to reach VO_2max at between 8 and 14 min. The VO_2max attainment criteria described by Howley, Bassett, and Welch (1995) were adopted. Respiratory parameters were continuously recorded using a portable ergospirometer (AEROSPORT-KB1-C, Ann Arbor, MI), with a sampling rate of 20 s. The gas analyzer was calibrated prior to each collection session according to the manufacturer's specifications (King, McLaughlin, Howley, Bassett, & Ainsworth, 1999).

To determine VT, ventilatory equivalents (VE/VO_2 and VE/VCO_2) for each participant were plotted over the corresponding VO_2 values. Three independent reviewers assessed VT graphs (Foster & Lucia, 2007; Powers, Dodd, Deason, Byrd, & Mcknight, 1983; Solberg, Robstad, & Skjonsberg, 2005).

Running Economy Determination Test. The RE test (in $ml.kg^{-1}.min^{-1}$) consisted of a 6-min run at 4.4 $m.s^{-1}$, on a treadmill (MOVEMENT-RT250, São Paulo, Brazil). This velocity corresponded to a physiological intensity of 89%

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of the average velocity at VT (5 m.s^{-1}), corresponding to a predominantly aerobic intensity for all participants. Individual RE was determined based on the mean VO_2submax values recorded during the last 2 min of the test. As in the incremental treadmill running protocol, the gas analyzer was calibrated prior to each collection session.

Electromyographic Recordings

Maximal activation of the rectus femoris (RF), vastus lateralis (VL), semitendinosus (ST), and short head of the biceps femoris (BF) muscles was determined for later normalization of the EMG signal obtained in the support and balance phases (%MVC), by performing a maximal voluntary contraction (MVC) test. These tests were conducted on land before and after the exercise protocol and consisted of a 5-s contraction of the muscle groups, in which each of the muscles mentioned acted as an agonist. Pretest MVC values were used for further normalization of the EMG signal (Knutson, Soderberg, Ballantyne, & Clarke, 1994).

The angles with highest torque production, measured with a goniometer (CARCI; São Paulo, Brazil), were identified based on the force-length relation (Fenn & Marsh, 1935) and adjusted so that they could be maintained during MVC performance against manual resistance in both flexion and extension directions. In addition, these angles were within the range of motion performed during the protocol. For the RF and ST muscles, the EMG signal was recorded as participants lay face-up with 90° of hip flexion. For the RF, the knee maintained 90° of flexion, with isometric contraction of the hip flexors. For the ST muscle, the knee maintained full extension (0°), with isometric contraction of the hip extensors. Afterward, participants were seated, with 90° of hip and 70° of knee flexion to record the EMG signal from the VL and BF muscles.

Pairs of Ag/AgCl pregelled surface electrodes (radius = 10 mm; TYCO HEALTHCARE, Hampshire, England) were applied after the innervation zone had been determined by using an EGF 4030 electric stimulator (CARCI, São Paulo, Brazil; Dainty & Norman, 1987). The electrode centers were placed 30 mm apart. Before each session, a digital multimeter was used to measure the interelectrode resistance level, which is considered suitable below 3,000 ohms. The reference electrode was positioned on the clavicle, and bipolar electrodes were placed 2 cm distal from the innervation zone.

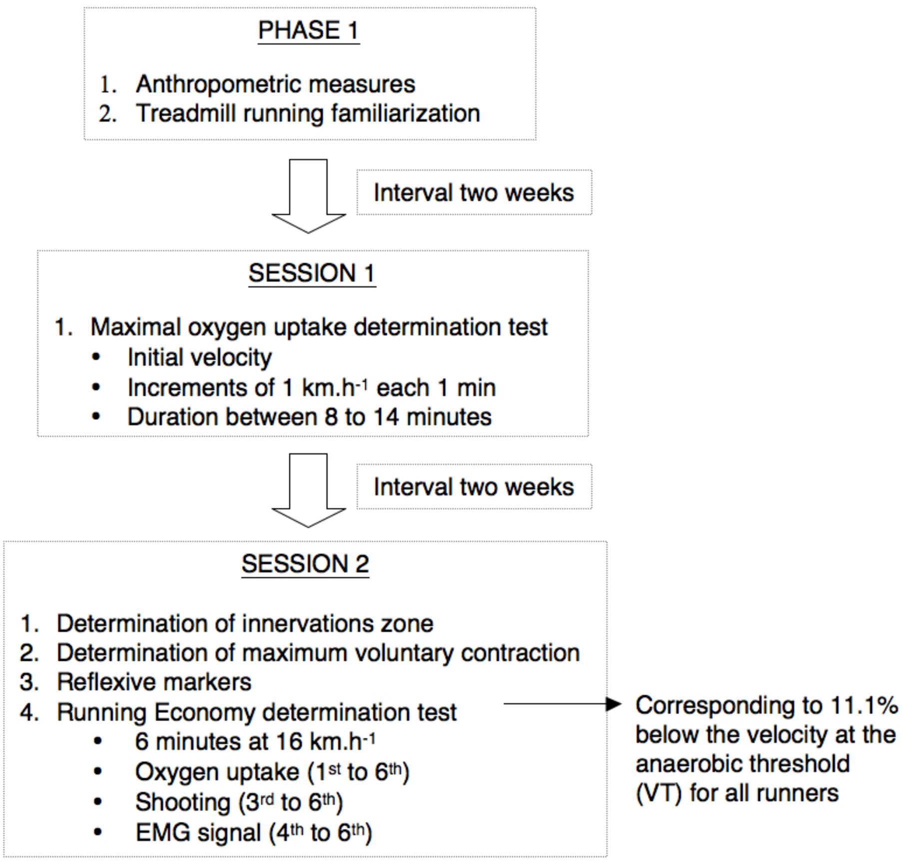

Figure 1. Experimental protocol.

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The EMG signals from the RF, VL, ST, and BF in the support and balance phases were recorded during the last 2 min of the run, using a portable electromyograph (MIOTEC, Porto Alegre, Brazil) with four channels (2000 Hz per channel) and a common rejection mode greater than 126 dB. The data were treated in SAD32 software (Mechanical Measurements Laboratory, UFRGS; Porto Alegre, Brazil). First, signal gains in the raw files were removed. Then the signal was digitally filtered using fifth-order band-pass Butterworth filters with a cut-off frequency between 20 and 450 Hz.

Visual inspection determined participant's foot strike and take-off events in three stride cycles, following the third stride after the fourth minute. Root mean square values (RMS) were obtained for the support and balance phases. The RMS value is used to quantify the EMG signal (Krogh-Lund & Jorgensen, 1991).

Kinematic Analysis

We adopted use of 13 reflective markers, 9 on the left sagittal plane (ear, shoulder, elbow, wrist, hip, knee, ankle, heel, and finger) and 4 in the posterior frontal plane of the left leg (2 points on the heel and ankle, 1 point placed one third from the distal portion of the gastrocnemius muscle, and 1 point where the gastrocnemius muscle originates, as described by Peyré-Tartaruga et al., 2009). During the RE test, kinematic variables (stride time, support time, balance time, stride length, relative stride length, stride frequency, internal knee and ankle angles at foot strike and take-off, maximum trunk flexion and maximum knee flexion in the support phase, range of elbow motion during the stride, maximal pronation of the subtalar joint, and vertical oscillation of the center of mass and external mechanical work) were recorded by two digital cameras (sagittal and posterior frontal planes, 120 Hz; Pulnix Progressive Scan, San Diego, CA). Magnitudes of the kinematic variables were recorded during the last 2 min of the run. The support and balance phases were visually identified during three stride cycles. The center of mass was calculated from the relative position of the body segments (Willems, Cavagna, & Heglund, 1995).

Recordings of the posterior frontal and left sagittal planes were digitized using DVIDEO software (Laboratory of Biomechanics & Institute of Computing, UNICAMP, São Paulo, Brazil). Running technique variables were calculated using three routines developed in MATLAB software, in which a Butterworth filter (fifth order), with a cut-off frequency of 5 Hz, was applied (Winter, 1990). The external mechanical work was also determined using the method from Willems, Cavagna, and Heglund (1995).

Statistical Analysis

Descriptive statistic calculations are presented as means and standard deviations. Normality of the data was assessed using the Shapiro-Wilk's test. We used Pearson's product-moment correlations to analyze the relationship between RE and the kinematic or muscular variables. For variables that presented significant values of $\alpha < .25$, we performed a multiple linear regression analysis to determine the influence of each independent variable on RE. Hosmer and Lemeshow (2000) recommended the significance level for this type of analysis.

Results

There were significant correlations between RE (M = 44.85 ml.kg^{-1}.min^{-1}, SD = 4.7) and performance variables (time at 10,000 m: M = 1,994 s, SD = 150; M VO_2max = 56.54 ml.kg^{-1}.min^{-1}, SD = 4.7; M VO_2 at VT = 49.60 ml.kg^{-1}.min^{-1}, SD = 5.4), demonstrating that RE can predict performance in long-distance running (see Figures 2, 3, and 4). The highest correlation was between RE and performance, because the variability of time at 10,000 m was lower (SD = 7.5% of average) compared to VO_2max (8.3%) and VO_2 at VT (10.8%). Mean velocity at VO_2max was 5.93 m.s^{-1} (SD = 0.3), and mean velocity at VT was 5.01 m.s^{-1} (SD = 0.3).

There were significant correlations between RE and some kinematic variables (vertical oscillation of the center of mass: r = .65; stride frequency: r = -.61; stride length: r = .61; balance time: r = .61; relative stride length: r = .46; range of elbow motion: r = .42; internal knee angle at foot strike: r = -.41; and internal ankle angle at foot strike: r = -.32) and between RE and muscular variables (RMS of the ST, r = .59, and RMS of the RF, r = -.36, at balance; and RMS of the ST at support, r = .34; see Table 1). In this study, 44.4% of kinematic variables and 66.6% of muscular variables showed a significant correlation with RE.

When using multiple regression analysis, 81% of the kinematic variables and 19% of the muscular variables were included in the RE prediction model. The overall predictive power of the multiple linear regression analysis model was 85.5%, with an estimated error of 2.52. The variables, stride frequency, stride length, internal knee angle at foot strike, percentage of maximum voluntary contractions of the ST muscle (%MVC ST) at support, vertical oscillation of the center of mass, and range of elbow motion showed the highest relationship with RE (see Table 2).

Discussion

We designed the present study to investigate the relationships between several biomechanical parameters and RE in endurance athletes. Running involves the conversion of muscular forces translocated through complex movement patterns that use all major muscles and joints

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in the body. Skill and precise timing are required for high performance running in which all movements have purpose and function (Anderson, 1996). Clearly, changing aspects of running mechanics that result in a runner using less energy at any given speed is advantageous to performance (Cavanagh & Williams, 1982).

Several relationships between biomechanical parameters and RE have been studied. The most frequently analyzed has been the relationship between stride length and/or stride frequency and RE (Nummela et al., 1994; Nummela et al., 2007; Williams & Cavanagh, 1987). In our study, stride frequency and length showed significant relationships with RE (r = -.61 and r = .61, respectively). According to the multiple regression analysis, these variables correspond to 28% and 23%, respectively, of the overall influence of biomechanical parameters on RE.

Cavanagh and Williams (1982) and Nummela et al. (2007) reported that the relatively efficient patterns used during running indicate either an adaptation to the chosen stride length through training (biomechanical adaptation) or a successful process of energy optimization (physiological adaptation). These adaptations result in a negative relationship between stride frequency and RE and a positive relationship between stride length and RE. Moreover, Bailey and Pate (1991), Saunders et al. (2004), Dallam, Wilber, Jadelis, Fletcher, and Romanov (2005), and Chen, Nosaka, Lin, Chen, and Wu (2009) showed that elite male distance runners had a better combination of stride frequency and length compared with good male distance runners and, consequently, a better RE. The strong correlations of stride frequency and length with RE and better combinations between stride frequency and stride length seen in our sample was probably due to their considerable professional experience, which corroborates findings in the literature.

Many studies have demonstrated that support and balance times are key factors affecting running energetics and mechanics (Morin, Samozino, Zameziati, & Belli, 2007). In their investigation of the relationships between support time, step frequency, and leg stiffness in human running, Morin et al. (2007) showed that support time, associated with balance time, could be a major determinant of this spring-mass characteristic of human running. Similarly, Clarke (1991) indicated that, during locomotion, the running technique is adjusted by changes to stride length and stride time, variables influenced by support and balance times. In our study, balance time presented a significant correlation (r = .61) and a predictive power of 3.2% with the RE. This correlation probably influenced the relationship between stride length and RE

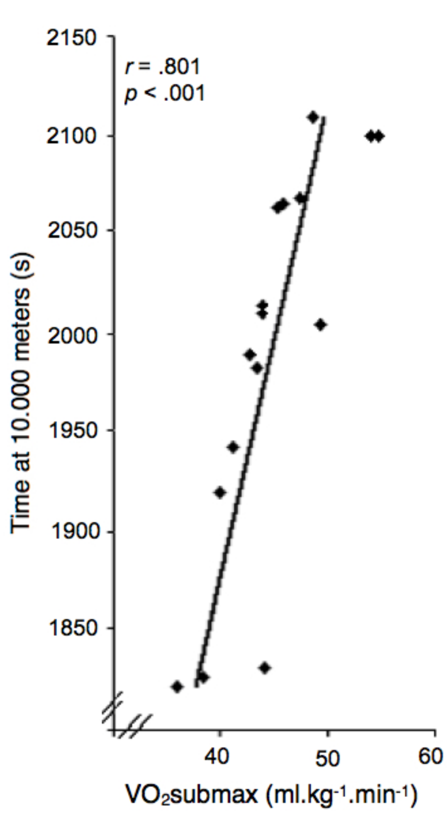

Figure 2. Correlation between submaximal oxygen consumption (VO_2submax) and performance.

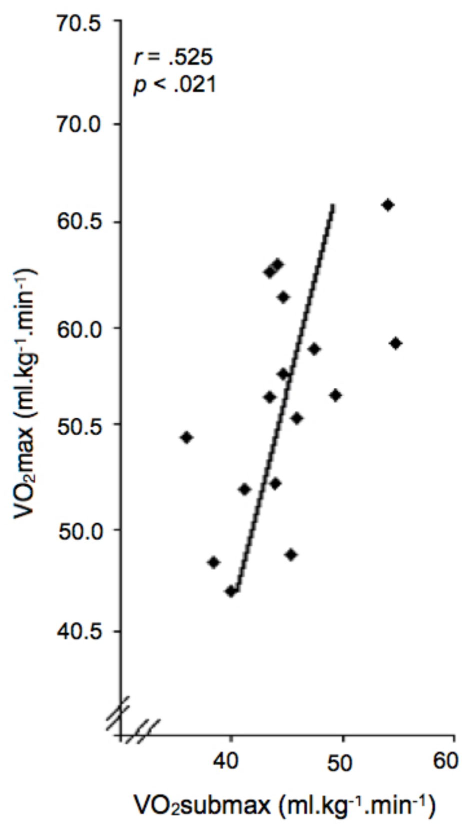

Figure 3. Correlation between submaximal oxygen consumption (VO_2submax) and maximal oxygen consumption (VO_2max).

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in our runners. The increase in balance time may result in decreased stride frequency, increased stride length, and, consequently, increased RE, as suggested by our results.

The mechanical work performed during exercise has often been studied in relation with RE. For this purpose, different models, such as the center of mass, segment-based, or kinetic models, have been used (Martin, Heise, & Morgan, 1993). In the center of mass model, vertical oscillation of the center of mass can be used to reflect the mechanical work. For example, Cavanagh et al. (1977) found that elite runners showed less vertical oscillation, were more symmetrical, and had better RE. However, Williams and Cavanagh (1987) analyzed the relationship between running mechanics, RE, and performance in 31 participants running at 3.6 $m.s^{-1}$ and reported that those with the best RE had greater vertical oscillation of the center of mass. Cavagna, Heglund, and Willems (2005) reported that less vertical oscillation results in: (a) higher stride frequency, (b) lower variation of external energy, and (c) higher internal work to accelerate segments within the center of mass, thus, increasing the metabolic cost of running. Our results are in agreement with this hypothesis, and there was a significant correlation ($r = .65$) between vertical oscillation of the center of mass and RE, as well as 7.2% predictive power, indicating that greater vertical oscillation is linked to a decrease in metabolic demand. We found significant correlations between internal knee and internal ankle angles, both at foot strike and RE ($r = -.41$ and $r = -.32$). These parameters predict 12.7% and 0.6% of RE in the multiple model, respectively. These findings corroborate those of Kyrolainen et al. (2001) and Gollhofer, Komi, Miyashita, and Aura (1987), who reported that greater muscular-tendon rigidity and lower degree of joint absorbency during athletic walking result in greater energy spent during treadmill running.

One interesting result of our study using kinematics analysis is the positive relationship between the range of

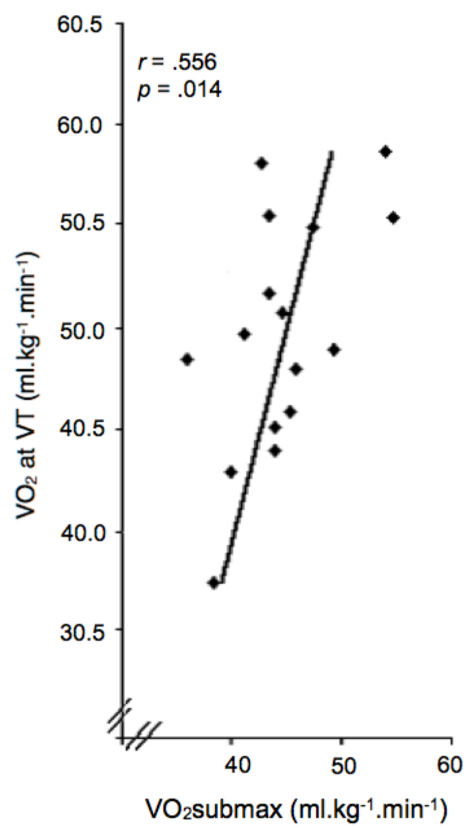

Figure 4. Correlation between submaximal oxygen consumption (VO_2submax) and VO_2 at ventilatory threshold (VT).

Table 1. Pearson product-moment correlations between running economy and biomechanical variables

Biomechanical variables	*M*	*SD*	*r*	*p*
Stride time (s)	0.69	0.04	.608	.012*
Support time (s)	0.21	0.01	.058	.832
Balance time (s)	0.48	0.03	.613	.012*
Stride length (m)	3.07	0.16	.608	.013*
Relative stride length (m)	3.74	0.24	.461	.072*
Stride frequency (pass/s)	1.45	0.08	-.613	.012*
Internal knee angle at foot strike (°)	159.26	6.12	-.409	.115*
Internal knee angle at take-off (°)	156.71	4.04	-.006	.984
Internal ankle angle at foot strike (°)	121.99	6.64	-.318	.230*
Internal ankle angle at take-off (°)	138.98	8.16	-.030	.913
Maximum knee flexion in the support phase (°)	128.12	12.32	-.239	.372
Maximum trunk flexion in the support phase (°)	14.86	4.32	.182	.500
Range of elbow motion (°)	38.84	12.60	.418	.107*
Maximal pronation of the subtalar joint (°)	11.69	4.56	.122	.653
Vertical oscillation of the center of mass (m)	9.52	1.00	.651	.006*
External mechanical work (J)	0.99	0.08	-.346	.289
%MVC RF at support	13.44	3.54	-.086	.750
%MVC VL at support	14.08	5.28	-.068	.802
%MVC ST at support	27.14	4.98	.340	.198*
%MVC BF at support	19.89	3.63	.095	.726
%MVC RF at balance	14.38	1.99	-.364	.166*
%MVC VL at balance	39.36	4.47	.037	.893
%MVC ST at balance	34.31	4.33	.593	.015*
%MVC BF at balance	30.14	4.35	.014	.959
EMG total (Mv)	1247.70	76.00	.340	.298

Note. M = mean; *SD* = standard deviation; %MVC = percentage of maximum voluntary contractions; RF = rectus femoris; VL = vastus lateralis; ST = semitendinosus muscle; BF = biceps femoris; and EMG = electromyographic.
*Variables with $\alpha < .25$.

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elbow motion during stride and RE (r = .42). Furthermore, we found a significant relationship (r = .54) between the range of elbow motion and stride length, indicating that, in part, participants with a shorter stride have a shorter arm movement. Arm movement is an important factor contributing to reducing oscillations in the transverse plane (Umberger, 2008) and increasing equilibrium of lower limb angular momentum over the body's vertical axis (Hinrichs, 1987) while running, resulting in enhanced global body equilibrium. Within this context, it has been observed that participants who use a short range of motion in the shoulder and elbow joints when running tend to have greater postural disequilibrium and, consequently lower RE (Tartaruga, Tartaruga, Ribeiro, Coertjens, Ribas, & Kruel, 2004).

Analysis of surface EMG activity has been used to study running technique (Hausswirth, Brisswalter, Vallier, Smith, & Lepers, 2000). When investigating kinematics, kinetics, and muscle activity in relation to RE at different running speeds, Kyrolainen et al. (2001) found significant correlations (range: r=.45–.48) between RE and muscular electrical activation, suggesting a positive relationship in runners with good running technique. However, Hausswirth, Bigard, and Guezennec (1997), compared the EMG signal of the VL muscle in 7 participants during the running section of a triathlon and at the end of a prolonged run performed at the same running velocity. They found greater values for VO_2submax, RMS, and heart rate during the prolonged run compared to the triathlon run, suggesting a negative relationship between RE and muscular electrical activation. The contrasting findings reported in these studies may be related to different motor activation patterns and, consequently, different running techniques.

In our study, the EMG values had an overall predictive power of 19.1% in relation to RE. There were significant correlations between RE and RMS values of the ST in the support (11.3% for r = .34) and balance (3.4% for r = .59) phases and between RE and RMS values of the RF in the balance phase (4.3% for r = -.36).

The ST is a biarticular muscle activated during hip extension and knee flexion. It allows the gluteus maximus, in the support phase, and the semimembranosus and BF muscles, in the balance phase, to diminish electrical muscular activation during the stride, consequently increasing RE (Thompson & Floyd, 1998). Furthermore, specific training to improve the neural component (motor unit recruitment patterns and augmentation in action potential conduction velocity over the muscle), to obtain greater efficiency from the ST muscle could also contribute to increasing RE and, thus, enhanced performance.

Besides acting as a knee extensor at the end of the balance phase, the RF acts as a powerful hip flexor, mainly during the contact phase, leading the center of mass to be projected forward (Montgomery, Pink, & Perry, 1994; Thompson & Floyd, 1998). Nevertheless, its action is considered auxiliary, due to the action of the iliopsoas muscle, mainly during knee extension at the end of the balance phase. Its contribution to knee extension is probably greater in relation to the hip flexion, making its relationship with the RE significant in the balance phase.

We found no significant relationship between the BF and VL muscles and RE. It is possible the ST actions during the support and balance phases and the RF in the balance phase are the main actions that influence RE, reducing the BF and VL actions (monoarticular muscles) in the support and balance phases. This may occur because the RF, according Montgomery et al. (1994) and Thompson and Floyd (1997), acts by eccentrically assisting the iliopsoas muscle during the support phase, decreasing the relationship with RE.

Table 2. Results of the multiple linear regression analysis

Biomechanical variables	Adjusted coefficients	Relationship (%)
Stride frequency	2.275	28.3
Stride length	1.848	23.0
Internal knee angle at foot strike	1.022	12.7
%MVC ST at support	0.911	11.3
Vertical oscillation of the center of mass	0.580	7.2
Range of elbow motion	0.447	5.6
%MVC RF at balance	0.346	4.3
%MVC ST at balance	0.276	3.4
Balance time	0.252	3.2
Internal ankle angle at foot strike	0.049	0.6
Relative stride length	0.021	0.4
Total		100.0

Note: %MVC = percentage of maximum voluntary contractions; ST = semitendinosus muscle; RF = rectus femoris muscle; variable related: oxygen uptake at 4.4 $m.s^{-1}$; variable excluded by the regression model: stride time (α > .05).

Conclusion

Our study showed changes in running technique and muscle activity related with RE in experienced 10,000-m runners at intensities below VT. While training for long-distance running, reduction in stride frequency and increase in stride length may enhance performance due to the increased RE. We identified exclusive biomechanical parameters to explain RE. This has important implications that should be considered when coaches or athletes make alterations to running technique.

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Authors' Notes

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